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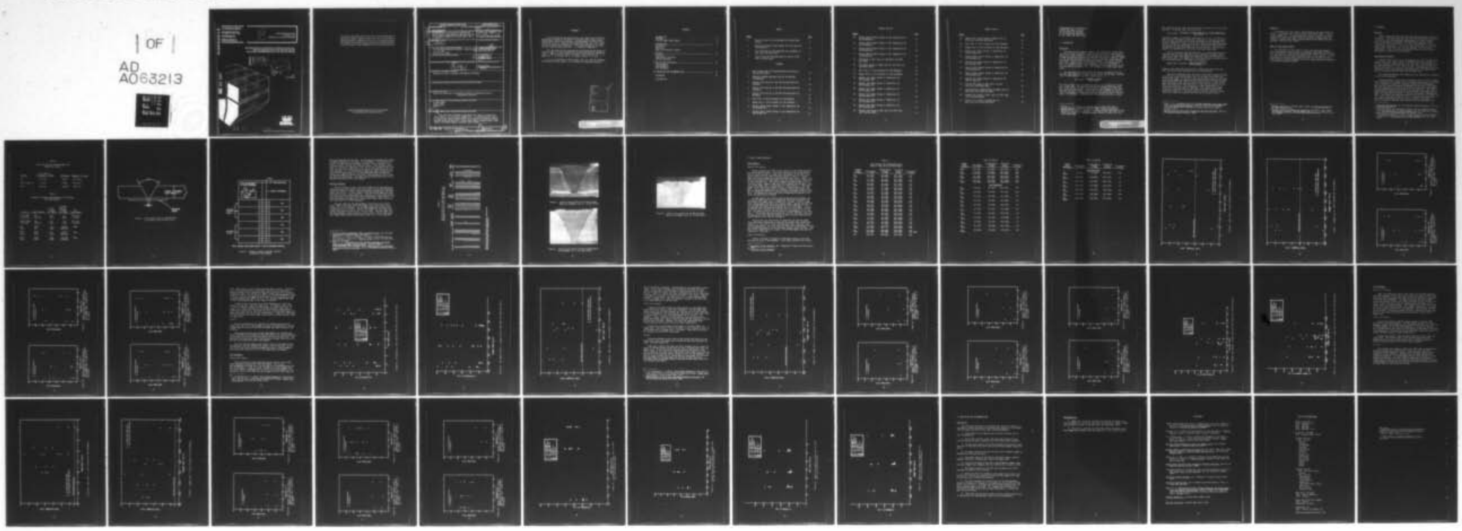

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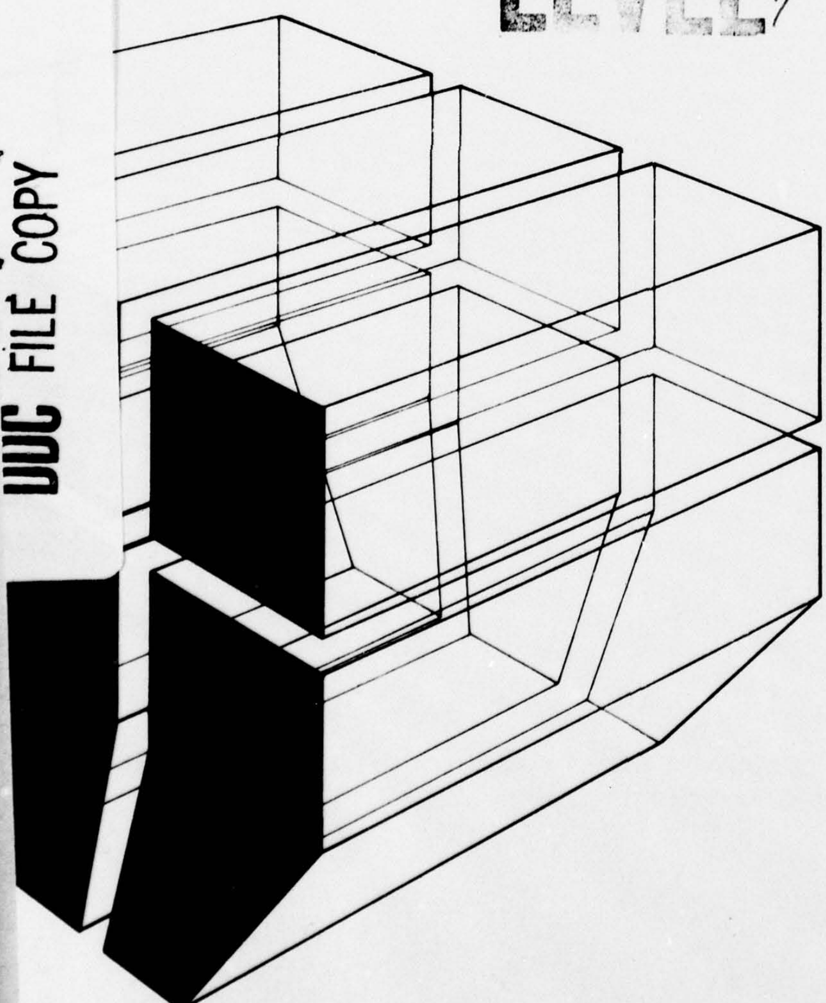
INTERIM REPORT M-248
November 1978
Weldability of Construction Materials

DETERMINATION OF THE EFFECT OF CURRENT AND TRAVEL SPEED OF SHIELDED METAL-ARC WELDING ON THE MECHANICAL PROPERTIES OF A36, A516, AND A514 STEELS

LEVEL II

by
R. A. Weber



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This study was performed to determine the limits on current and travel speed -- in particular nugget area -- as defined by the results of tensile and impact properties of butt joint welds produced by manual shielded metal-arc welding in carbon steel (A36), pressure-vessel steel (A516), and high-strength, low-alloy steel (A514).

FOREWORD

This investigation was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Materials, Research, and Development for Military Construction"; Task T7, "Application Engineering"; Work Unit 007, "Weldability of Construction Materials." The applicable QCR is 3.07.024. The OCE Technical Monitor was Mr. I. A. Schwartz, DAEN-MPE-T.

This investigation was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). CERL personnel directly involved in the study were Mr. R. A. Weber, Mr. F. H. Kisters, Ms. R. E. Hannan, and Mr. E. P. Cox.

Dr. G. R. Williamson is Chief of EM. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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OF A36, A516, AND A514 STEELS

1 INTRODUCTION

Background

Shielded metal-arc welding (SMAW) is the predominant form of welding used in Corps of Engineers construction; it is used about twice as often as any other method in field and shop fabrication. The technology of SMAW has advanced considerably from the early days of welding. There are now sophisticated welding power supplies and high-quality welding electrodes. Despite these improvements, however, the quality of weldments still depends mainly on the operator's skill and experience. Thus, the operator's experience is generally the deciding factor in setting the welding variables, i.e., arc voltage, arc current, and travel speed.

For many years, the only control on welding has been by limiting the heat input measured in Joules (J) per linear inch of weld. The heat input is determined by using this simple relation:

$$\text{Heat Input} = \frac{\text{Voltage x Current}}{\text{Travel Speed}}$$

The limit on heat input has generally been set to a maximum of 55,000 J/in. (2160 J/mm). Dorschu[1] and Schultz and Jackson[2] have shown that, for a given set of parameters, the strength and toughness of the weldment can vary considerably. Dorschu has devised a method for controlling the strength of weldments by limiting the cooling rate of the weld beads. He developed a formulation for the cooling rate that includes

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1 Dorschu, K. E., "Control of Cooling Rates in Steel Weld Metal," Welding Journal, Volume 47 (February 1968), Research Supplement.

2 Shultz, B. L., and C. E. Jackson, "Influence of Weld Bead Area on Weld Mechanical Properties," Welding Journal, Volume 53 (June 1974), Research Supplement.

the variables of heat input, plate thickness, and the initial plate temperature. In general form, the relation is:

$$\text{Cooling Rate} = \frac{\text{Thickness} \times (\text{Test Temperature} - \text{Plate Temperature})}{\text{Heat Input}}$$

Dorschu has shown with ASTM A201 mild steel up to 2 in. (5.1 cm) thick that the yield strength of weld metal decreases at slow cooling rates, while at high cooling rates the yield strengths can be increased from 15,000 to 20,000 psi (103.4 to 137.9 MPa). Shultz and Jackson have gone one step further and determined that for a 5Ni-Cr-Mo-V steel, the arc voltage has no significant effect on the cooling rate. Cooling rates appear to be determined by the current and travel speed only.

Shultz and Jackson conclude that there is a clear relationship between cooling rate and nugget area which, therefore, becomes a useful indicator of weld metal mechanical properties under the influence of weld cooling rate. The nugget area is defined as the cross-section area of a single weld bead. The nugget area equation is:

$$\text{Nugget Area} = \text{Constant} \times \frac{(\text{Arc Current})^{1.55}}{(\text{Travel Speed})^{0.903}}$$

However, their work does not provide for determining the limits that will insure the proper strength levels of the weld metal.

The Corps of Engineers has instituted a three-part research program in an effort to determine these limits for various plate steels and welding electrodes. In the first part of the study, limits on the electrode travel speed and voltage for shielded metal-arc welding electrodes were determined on the basis of bead-on-plate studies.[3] These limits were established using amperage values in the American Welding Society (AWS) specifications.[4] The second part of the investigation is intended to refine the limits of amperage, travel speed, and voltage using their interrelationship with nugget area based on weld joint mechanical properties. The third part will seek to confirm or adjust these with regard to restraint and cracking in the weld joints.

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[3] Weber, R. A., Determination of Arc Voltage, Amperage, and Travel Speed Limits by Bead on Plate Welding, Technical Report M-197/ADA033684 (U.S. Army Construction Engineering Research Laboratory [CERL], December 1976).

[4] Specification for Mild Steel Covered Arc Welding Electrodes, AWS A5.1-69 (American Welding Society, 1969).

Objective

The objective of this report, which addresses the second phase of study, is to present the limits on current and travel speed -- in particular nugget area -- as defined by the results of tensile and impact properties of butt joint welds produced by manual shielded metal-arc welding in carbon steel (A36), pressure-vessel steel (A516), and high-strength, low-alloy steel (A514).

Mode of Technology Transfer

The information in this report is part of a long-term research effort designed to maintain Corps of Engineers Guide Specifications CE-5141 and CE-15116,[5] and Technical Manuals (TM) 5-805-7 and 9-237,[6] which are concerned with producing acceptable welds in construction. This information will serve as part of the data base for use with the weld quality monitor under development at the U.S. Army Construction Engineering Research Laboratory (CERL).

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5 Welding, Structural, CE-05141 (April 1975); and Welding, Mechanical, CE-15116 (October 1974).

6 Welding; Design, Procedures and Inspection TM 5-805-7 (March 1968); and Operator's Manual: Welding Theory and Application, TM 9-237 (October 1976).

2 APPROACH

Materials

Table 1 identifies the plate steel and electrodes used in this investigation. Electrode types were selected for use with the plate material based on the AWS Structural Welding Code[7] and common usage for Corps of Engineers construction. One plate steel type was chosen from each of the three categories of steel used frequently in Corps of Engineers construction: (1) carbon steel (ASTM A36), (2) pressure-vessel steel (ASTM A516), and (3) high-strength, low-alloy steel (ASTM A514F). Table 2 presents the specification limits for each of the materials used in this investigation.

Experimental Procedure

The weld joint used in this investigation was a 60° included angle, single V-butt joint with a 1/8-in. (3.2-mm) root opening (Figure 1). The weld length was approximately 18 in. (457 mm). The completed joint was approximately 12 x 18 in. (305 x 457 mm). Each material type required nine joints for a total of 27 plates. All plate material was cut and beveled using an oxyacetylene cutting apparatus and then surface-ground to remove oxides and slag from the joint area.

Each completed weldment was nondestructively examined for soundness using X-ray radiography.

One macrospecimen, three tensile specimens, and six impact (dynamic tear) specimens were machined from the completed sound weld. See Figure 2 for a schematic of specimen locations as machined from weldments. When the heat of welding warped the weldment to the extent that dynamic tear (DT) specimens could not be machined from the plate, three Charpy V-notch specimens were substituted for each DT specimen. The impact specimens were machined so that half were notched in weld metal and the other half were notched adjacent to the weld in the heat affected zone (HAZ). The impact specimens were tested at $70^{\circ}F$ ($21^{\circ}C$), $32^{\circ}F$ ($0^{\circ}C$), and $0^{\circ}F$ ($-18^{\circ}C$) according to ASTM E-23[8] for the Charpy V-Notch specimens and ASTM Proposed Method[9] for the 5/8-in. (16-mm) DT specimens. Two of the tensile specimens were machined from the weld metal; the

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7 Structural Welding Code, D1-1-75 (American Welding Society, 1975; revised 1976 and 1977).

8 "Standard Methods for Notched Bar Impact Testing of Metallic Materials," 1976 Annual Book of ASTM Standards, Part 10, ASTM E23-72 (American Society for Testing and Materials [ASTM], 1976).

9 "ASTM Proposed Method for 5/8-in. (16-mm) Dynamic Tear Test of Metallic Materials," 1976 Annual Book of ASTM Standards, Part 10 (ASTM, 1976).

Table 1

Materials Used for Shielded Metal-Arc Welded Butt Joints

ASTM No.	Plate Material Thickness, in. (mm)	Electrode	Diameter, in. (mm)
A36	3/4 (19)	E7018	1/8 (3.2)
A516, Grade 70	1 (25.4)	E7018	1/8 (3.2)
A514	3/4 (19)	E11018	1/8 (3.2)

Table 2

Mechanical Property Requirements for Electrodes and Plate Material

Material	Specification	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	CVN Requirements
E7018 SMAW Electrodes	AWS A5.1-69	60 (416)	72 (494)	20 ft-lb. at-20°F
E11018 SMAW Electrodes	AWS A5.5-69	97 (669)	110 (758)	20 ft-lb. at-60°F
A36 Plate	ASTM A36	36 (248)	58-80 (400-552)	None
A516 Plate	ASTM A516	38 (262)	70-90 (483-621)	None
A514 Plate	ASTM A514F	100 (689)	110-130 (758-896)	None

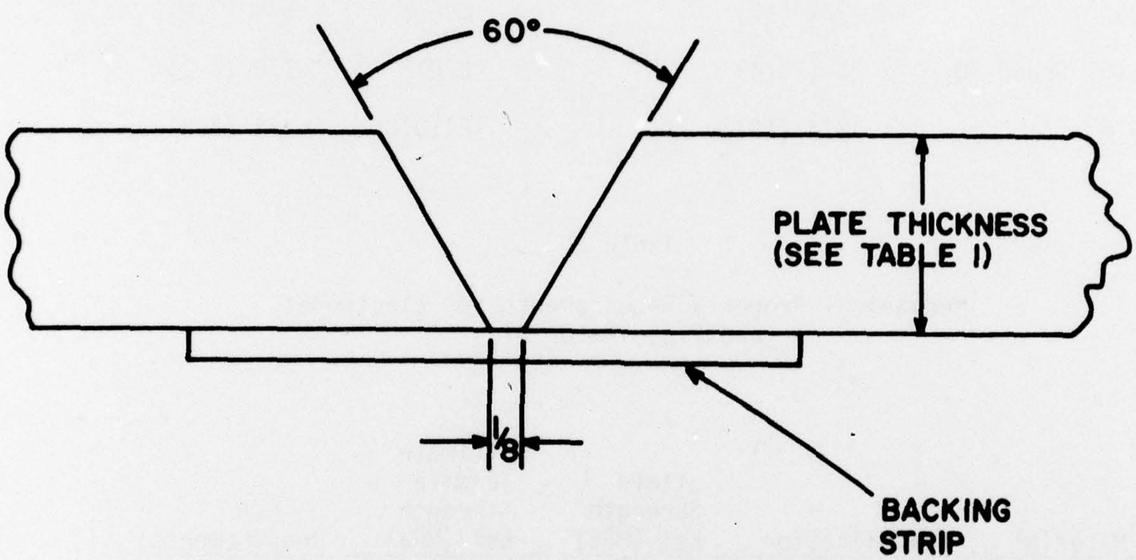

Figure 1. Joint design used for shielded metal-arc welding of A36 and A516 steel.

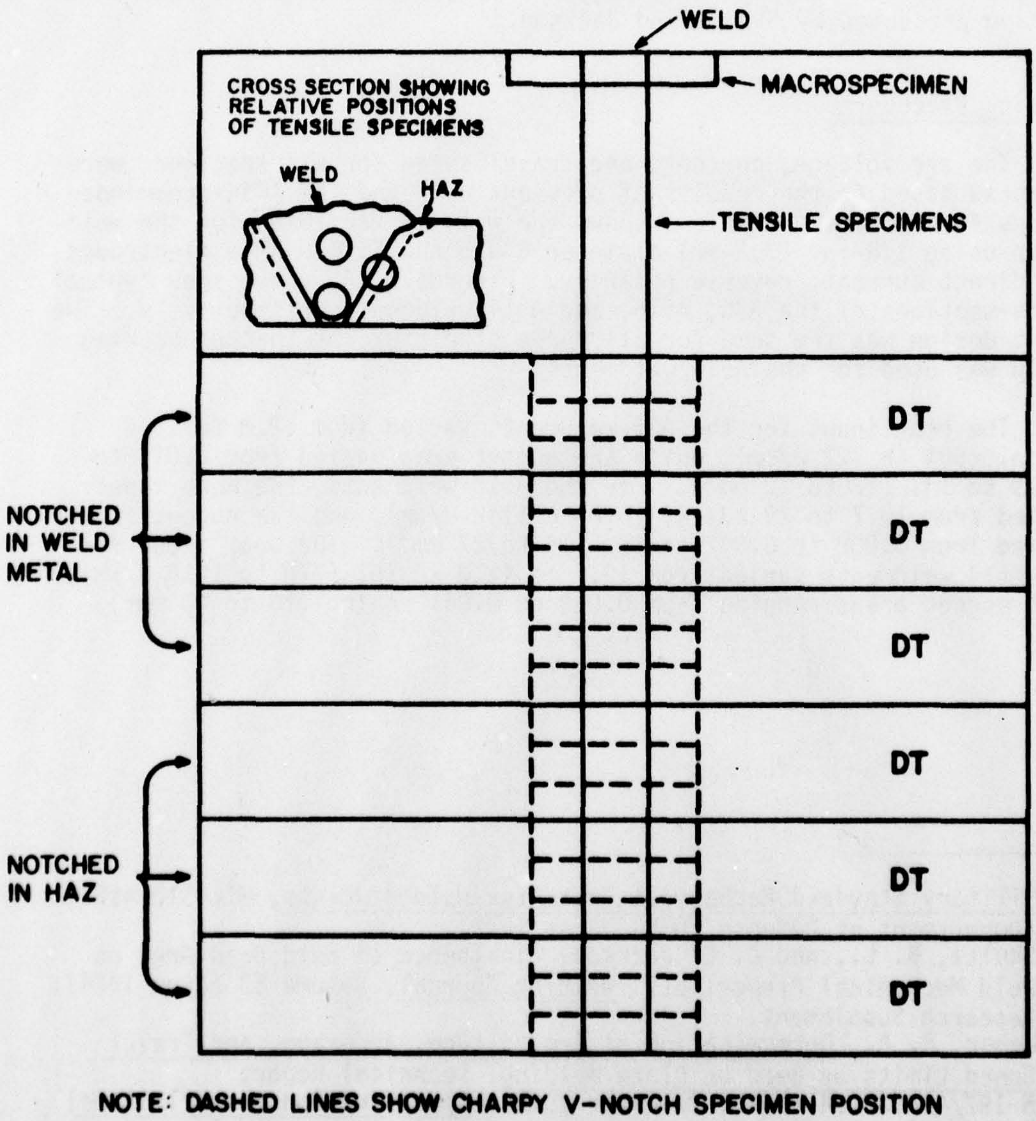

Figure 2. Schematic showing specimen location as machined from weldment.

third was machined from the HAZ. All the tensile specimens were tested at ambient temperature according to MIL-STD-418C.[10] The tensile test results include the yield strength, ultimate tensile strength, true fracture stress, and the true fracture strain. (True fracture strain, which is the natural logorithm of the initial area divided by the final area, was used as an indication of the ductility exhibited by the tensile specimen. It is a dimensionless number and shows increasing ductility with higher numbers.) The macrospecimens were polished and etched using ammonium persulfate etchant, and examined for small flaws not shown by radiography. The nugget area was determined using the nomograph presented by Shultz and Jackson.[11]

Welding Procedure

The arc voltage, current, and travel speed for all specimens were selected based on the results of previous work and the AWS-recommended values for current.[12] Table 3 shows the welding variables for the weldments using 1/8-in. (3.2-mm) diameter E7018 and E11018 SMAW electrodes and direct current, reverse polarity. Figures 3, 4, and 5 show typical cross-sections of the A36, A516, and A514 weldments, respectively. The joint design was the same for all three steels except that no backing strip was used for the A514 weldments.

The heat input for the A36 weldments varied from 12.8 to 19.6 kJ/in. (504 to 722 J/mm), while the nugget area varied from 0.019 to 0.029 sq in. (12 to 19 mm^2). For the A516 weldments, the heat input varied from 15.7 to 29 kJ/in. (618 to 1142 J/mm), and the nugget area varied from 0.002 to 0.042 sq in. (14 to 27 mm^2). The heat input for the A514 weldments varied from 19.7 to 41.3 kJ/in. (776 to 1616 J/mm), with nugget areas ranging from 0.028 to 0.061 sq in. (18 to 40 mm^2).

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10 Military Standard Mechanical Tests for Welded Joints, MIL STD-418C (Department of Defense [DOD], June 1972).

11 Shultz, B. L., and C. E. Jackson, "Influence of Weld Bead Area on Weld Mechanical Properties," Welding Journal, Volume 53 (June 1974), Research Supplement.

12 Weber, R. A., Determination of Arc Voltage, Amperage, and Travel Speed Limits by Bead on Plate Welding, Technical Report M-197/ADA033684 (CERL, December 1976), Specification for Mild Steel Covered Arc Welding Electrodes, AWS A5.1-69 (American Welding Society, 1969).

Table 3

Weld Variables for Shielded Metal-Arc
Weldments of A36, A516, and A514 Steel

Specimen	Material	Electrode	Voltage* (Volts)	Current+ (Amperes)	Travel* Speed IPM (min/sec)	Heat Input KJ/in. (J/mm)	Nugget Area sq. in. (mm^2)	Plate Thickness in. (mm)	Number of passes
B3	A36	E7018	24	140	10.3 (4.33)	19.6 (772)	0.029 (19)	.75 (19)	30
B4	A36	E7018	24	140	15.7 (6.59)	12.8 (504)	0.020 (13)	.75 (19)	56
B6	A36	E7018	26	165	13.5 (5.67)	19.1 (752)	0.029 (19)	.75 (19)	37
B7	A36	E7018	22	115	11.5 (4.83)	13.2 (520)	0.019 (12)	.75 (19)	54
B8	A36	E7018	25	160	15.6 (6.55)	15.4 (606)	0.024 (15.5)	.75 (19)	40
B9	A36	E7018	23	115	9.1 (3.82)	17.4 (685)	0.024 (15.5)	.75 (19)	32
B10	A516	E7018	23	115	10.1 (4.24)	15.7 (618)	0.022 (14)	1.00 (25.4)	52
B11	A516	E7018	23.5	140	10.8 (4.54)	18.3 (720)	0.028 (18)	1.00 (25.4)	46
B12	A516	E7018	26	165	11.4 (4.79)	22.6 (890)	0.034 (22)	1.00 (25.4)	45
B13	A516	E7018	22	115	6.3 (2.65)	24.1 (949)	0.033 (21.5)	1.00 (25.4)	48
B14	A516	E7018	23	140	8.4 (3.53)	23.0 (906)	0.035 (22.5)	1.00 (25.4)	43
B15	A516	E7018	26	160	8.6 (3.61)	29.0 (1142)	0.042 (27)	1.00 (25.4)	37
B16	A514	E11018	22	115	7.7 (3.23)	19.7 (776)	0.028 (18)	.75 (19)	22
B17	A514	E11018	23	140	8.6 (3.61)	22.5 (886)	0.034 (22)	.75 (19)	22
B18	A514	E11018	25	165	8.7 (3.65)	28.5 (1122)	0.044 (28)	.75 (19)	22
B19	A514	E11018	22	115	5.3 (2.23)	28.6 (1126)	0.039 (25)	.75 (19)	9
B20	A514	E11018	23	140	6.2 (2.60)	31.2 (1228)	0.046 (30)	.75 (19)	11
B21	A514	E11018	25	165	6.0 (2.52)	41.3 (1626)	0.061 (40)	.75 (19)	14

*Voltage and travel speed were selected based on previous work.
+Current selected based on AWS recommendations.

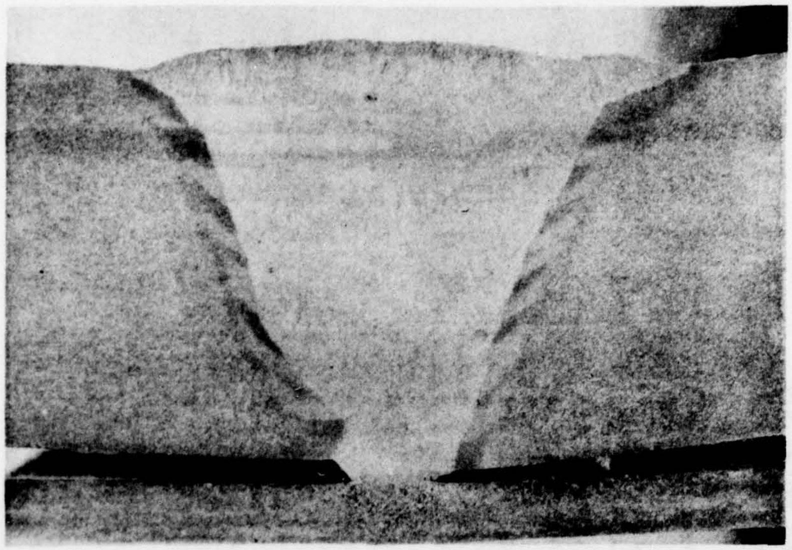

Figure 3. Typical cross-section of the A36 shielded metal-arc weldments (3/4 in. [19 mm] thick).

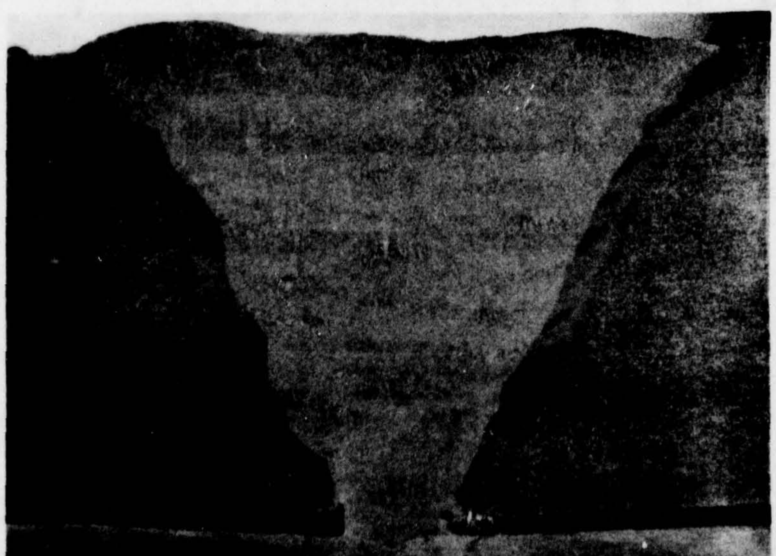

Figure 4. Typical cross-section of A516 shielded metal-arc weldments (1 in. [25.4 mm] thick).

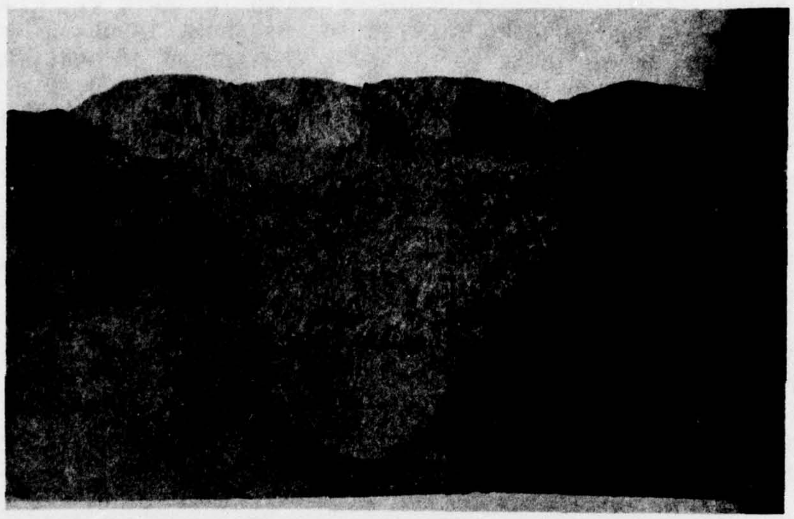

Figure 5. Typical cross-section of the A514 shielded metal-arc weldments (3/4 in. [19 mm] thick).

3 RESULTS AND DISCUSSION

A36 Weldments

Tensile Test Results

Table 4 presents the tensile test results for the E7018 weld metal and the A36 HAZ specimens. The results show that the all-weld metal tensile properties meet or exceed the requirements of the AWS 5.1-69 specification for mild steel electrodes shown in Table 2. Figure 6 shows the yield strength data plotted against heat input. There is no definitive trend to the data points over the spread of heat inputs used in this investigation. The yield strengths are spread over a 15 ksi (103 MPa) range. However, when the yield strengths are plotted vs the calculated nugget area, a trend begins to show (Figure 7). With small nugget areas, the yield strength is high -- greater than 70 ksi (483 MPa) -- but as the nugget area is increased, the yield strength drops off and approaches the minimum specification requirement of 60 ksi (416 MPa). Following this trend, the yield strength would eventually drop below the specification minimum.

The HAZ tensile test results show increasing yield strength with increasing nugget area until it approaches the yield strength of the weld metal at a nugget area of 0.029 sq in. (19 mm^2). For all nugget areas investigated, the HAZ yield strength shows a marked increase over the reported base metal yield strengths of 37 ksi (255 MPa).[13] The minimum HAZ yield strength obtained was 46.2 ksi (3197 MPa). The heat of welding also increases the ultimate tensile strength (UTS) of the HAZ. The reported UTS for A36 base metal is approximately 71 ksi (490 MPa).[14] The minimum HAZ UTS obtained was 70.6 ksi (487 MPa), while the maximum was 81.9 ksi (565 MPa), which is above the base plate maximum specification for UTS (80 ksi [552 MPa]).

The test data are insufficient to determine the optimum nugget area; additional information is required for nugget areas larger than 0.030 sq in. (19.5 mm^2). With this additional data, the upper limit could be determined. The limit would be based on the HAZ properties and the minimum requirements of the electrode strength specifications. With the results presented in this report, the minimum nugget area would be 0.025 sq in. (16.2 mm^2).

Impact Test Results

Figures 8 through 13 present the CVN impact energy vs test temperature for each of the weldments. Each figure contains the all-weld

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[13] Structural Alloys Handbook, Vol 1 (Mechanical Properties Data Center, 1977).

[14] Structural Alloys Handbook.

Table 4

Tensile Data for Shielded Metal-Arc Welds of A36, A516, and A514 Steel

Specimen Code (Weld Metal)	Yield Strength, ksi (MPa)	Ultimate Tensile Strength, ksi (MPa)	True Fracture Stress, ksi (MPa)	True Strain at Fracture	
B3	72.2 (496)	86.1 (593)	191.1 (1318)	1.27	
(A36)	63.7 (441)	85.9 (593)	181.5 (1255)	1.23	
B4	77.4 (531)	89.3 (614)	185.5 (1282)	1.21	
(A36)	73.2 (503)	89.0 (614)	193.7 (1338)	1.23	
B6	69.5 (476)	86.1 (593)	183.7 (1269)	1.15	
(A36)	76.6 (531)	89.3 (614)	191.1 (1317)	1.26	
B7	72.4 (496)	86.7 (600)	188.5 (1300)	1.29	
(A36)	75.0 (517)	87.6 (607)	189.3 (1305)	1.23	
B8	67.4 (462)	81.7 (565)	190.8 (1316)	1.35	
(A36)	74.8 (517)	86.9 (600)	185.2 (1277)	1.20	
B9	70.2 (483)	84.7 (586)	191.8 (1322)	1.29	
(A36)	78.4 (538)	89.6 (621)	185.9 (1282)	1.11	
B10	69.6 (483)	81.9 (565)	198.5 (1369)	1.39	
(A516	75.8 (524)	90.2 (621)	185.0 (1276)	1.05	
B11	68.7 (476)	82.8 (572)	181.6 (1252)	1.25	
(A516)	76.8 (531)	87.6 (607)	182.3 (1257)	1.24	
B12	68.4 (469)	81.8 (565)	188.7 (1301)	1.33	
(A516)	73.6 (510)	85.2 (586)	189.7 (1308)	1.29	
B13	68.4 (469)	82.2 (565)	190.4 (1313)	1.35	
(A516)	74.2 (510)	85.7 (593)	184.9 (1275)	1.29	
B14	66.7 (462)	81.7 (565)	182.5 (1258)	1.31	
(A516)	72.2 (496)	83.2 (572)	186.1 (1283)	1.32	
B15	63.7 (441)	78.2 (538)	186.5 (1286)	1.38	
(A516)	69.4 (476)	80.1 (552)	162.0 (1117)	1.09	
B16	113.4 (779)	123.8 (855)	199.3 (1374)	0.83	
(A514)	114.5 (786)	120.9 (834)	212.6 (1466)	0.96	
B17	114.4 (786)	124.5 (855)	215.6 (1487)	0.90	
(A514)	120.3 (827)	125.5 (862)	162.9 (1123)	0.31	defect
B18	105.4 (724)	120.3 (827)	211.0 (1455)	0.93	

Table 4 (cont'd)

Specimen Code (Weld Metal)	Yield Strength, ksi (MPa)	Ultimate Tensile Strength, ksi (MPa)	True Fracture Stress, ksi (MPa)	True Strain at Fracture
(A514)	106.9 (738)	115.6 (800)	206.5 (1424)	0.97
B19	117.4 (807)	127.8 (883)	224.5 (1544)	0.85
(A514)	127.8 (883)	137.8 (950)	247.0 (1703)	0.80
B20	114.3 (786)	126.8 (876)	210.5 (1451)	0.90
(A514)	110.3 (758)	120.7 (834)	205.5 (1417)	0.79
B21	106.3 (731)	119.5 (820)	210.1 (1449)	0.91
(A514)	96.4 (662)	109.3 (752)	185.0 (1276)	0.75
		Heat Affected Zone		
B3 (A36)	62.2 (427)	80.1 (552)	159.7 (1101)	0.99
B4 (A36)	49.8 (338)	74.2 (510)	141.7 (977)	0.92
B6 (A36)	59.5 (407)	78.3 (538)	157.7 (1087)	0.97
B7 (A36)	46.2 (317)	70.6 (487)	146.3 (1009)	1.04
B8 (A36)	66.6 (462)	81.9 (565)	169.2 (1167)	1.01
B9 (A36)	52.3 (359)	74.7 (517)	145.3 (1002)	0.92
B10 (A516)	73.9 (510)	87.6 (607)	188.5 (1300)	1.20
B11 (A516)	54.8 (379)	80.1 (552)	157.9 (1089)	1.01
B12 (A516)	53.3 (365)	76.5 (531)	168.0 (1158)	1.11
B13 (A516)	69.3 (476)	84.5 (586)	190.7 (1315)	1.24
B14 (A516)	64.8 (448)	84.2 (579)	170.6 (1176)	1.05

Table 4 (cont'd)

Specimen Code (Weld Metal)	Yield Strength, ksi (MPa)	Ultimate Tensile Strength, ksi (MPa)	True Fracture Stress, ksi (MPa)	True Strain at Fracture
		Heat Affected Zone		
B15 (A516)	59.9 (414)	79.2 (545)	151.0 (1041)	0.99
B16 (A514)	116.8 (807)	124.8 (862)	239.5 (1651)	1.17
B17 (A514)	109.9 (758)	118.8 (820)	235.5 (1624)	1.21
B18 (A514)	115.4 (793)	123.3 (848)	235.9 (1627)	1.13
B19 (A514)	100.6 (696)	119.7 (827)	207.3 (1429)	0.78
B20 (A514)	121.8 (841)	129.1 (890)	207.9 (1433)	0.74
B21 (A514)	100.5 (689)	112.3 (772)	227.3 (1567)	1.26

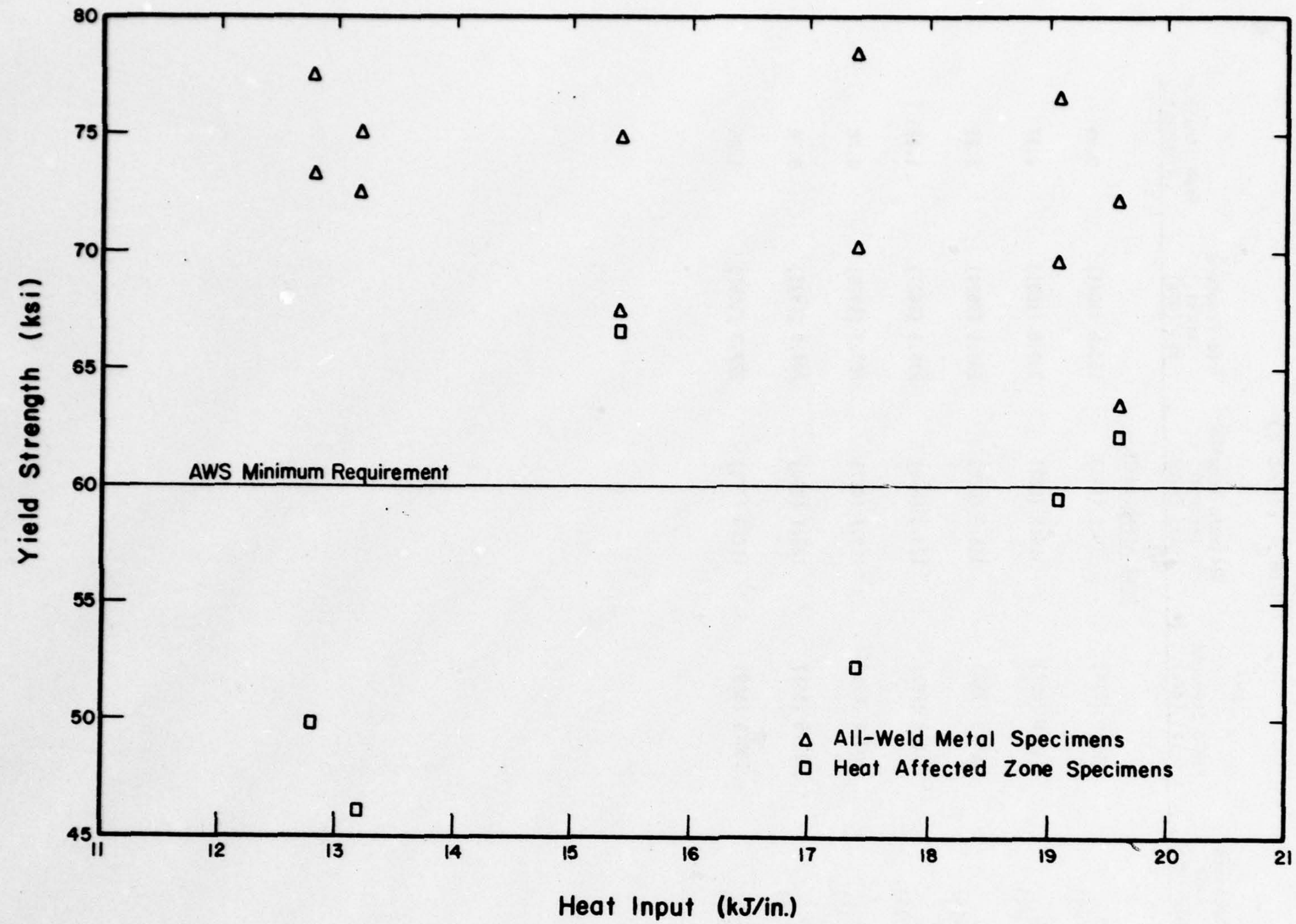

Figure 6. Heat input vs yield strength for A36 weldments.

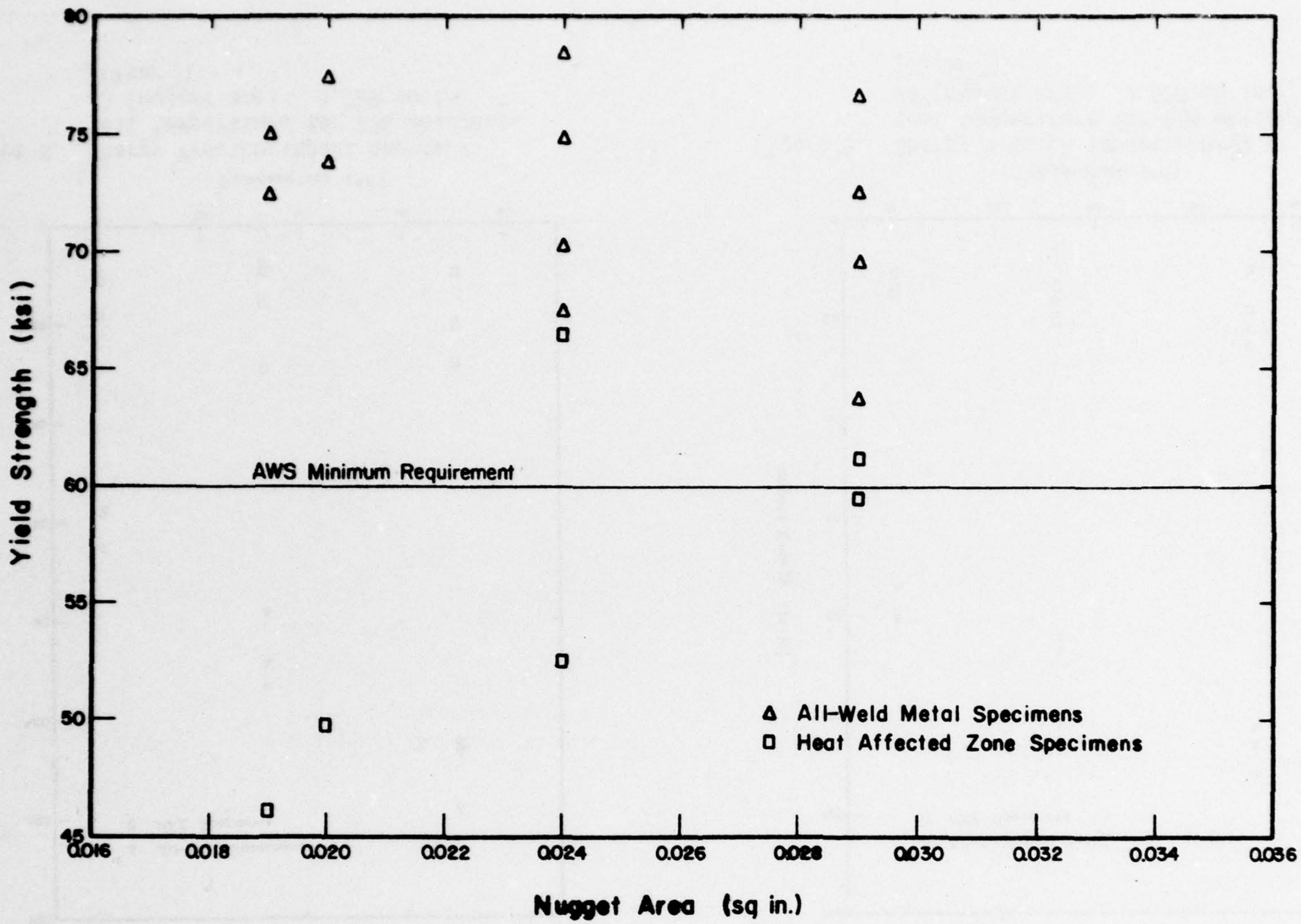

Figure 7. Nugget area vs yield strength for A36 weldments.

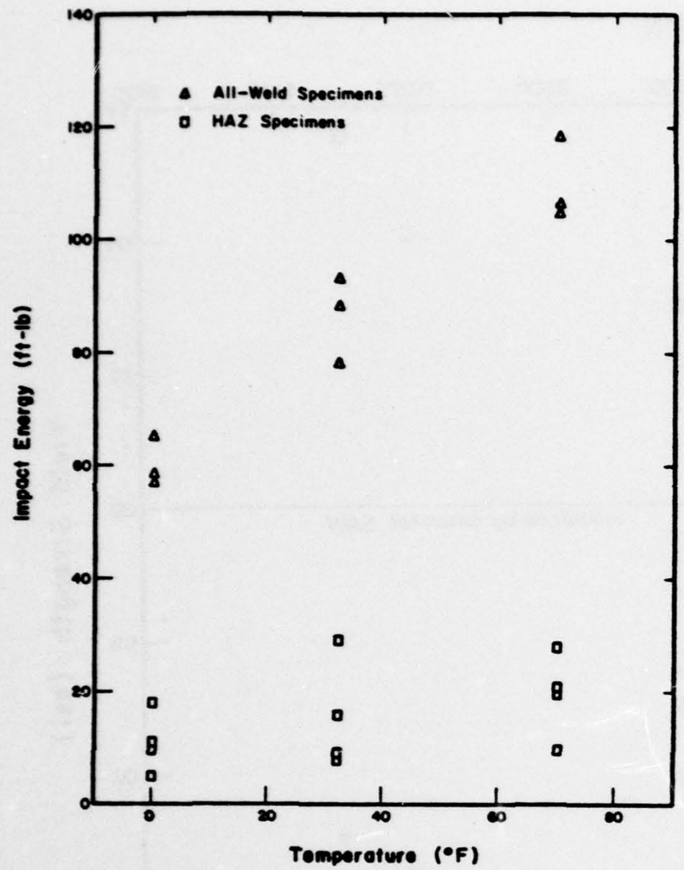

Figure 8. Charpy V-notch impact energy vs test temperature for A36 weldment-B3 (nugget area: 0.029 sq in. [19 mm^2]).

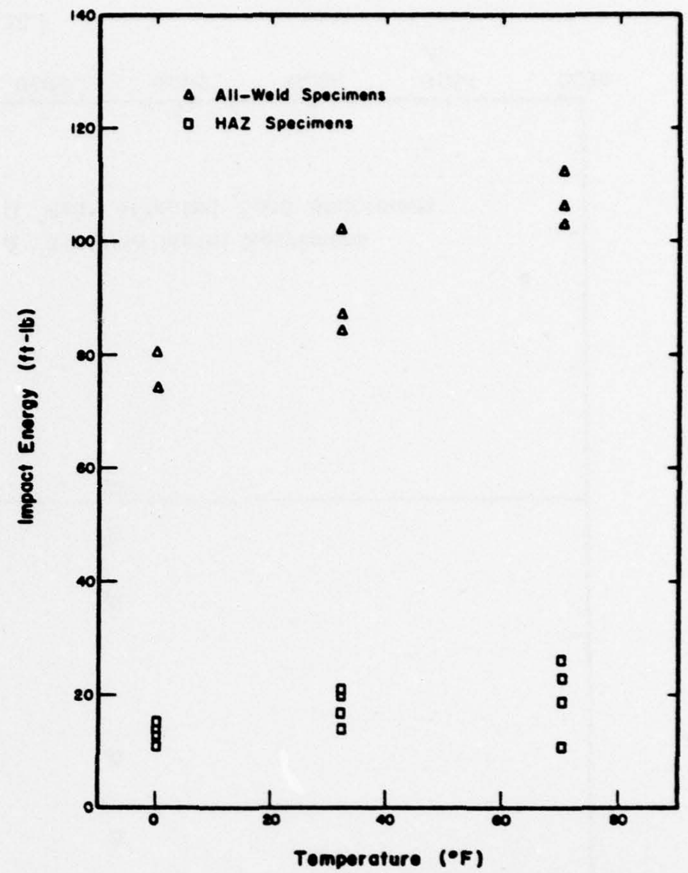

Figure 9. Charpy V-notch impact energy vs test temperature for A36 weldment-B4 (nugget area: 0.020 sq in. [13 mm^2]).

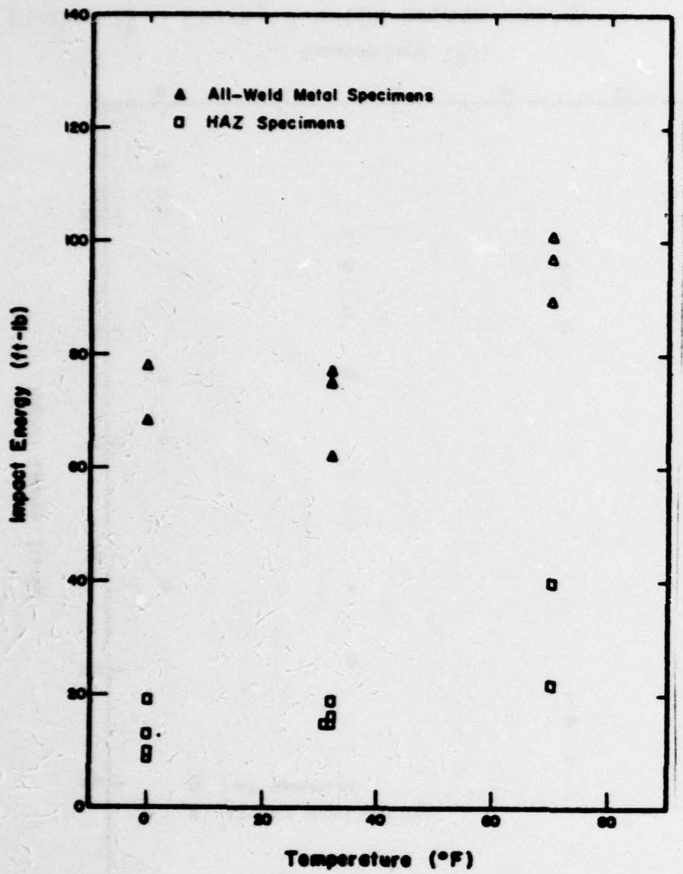

Figure 10. Charpy V-notch impact energy vs test temperature for A36 weldment-B6 (nugget area: 0.029 sq in. [19 mm²]).

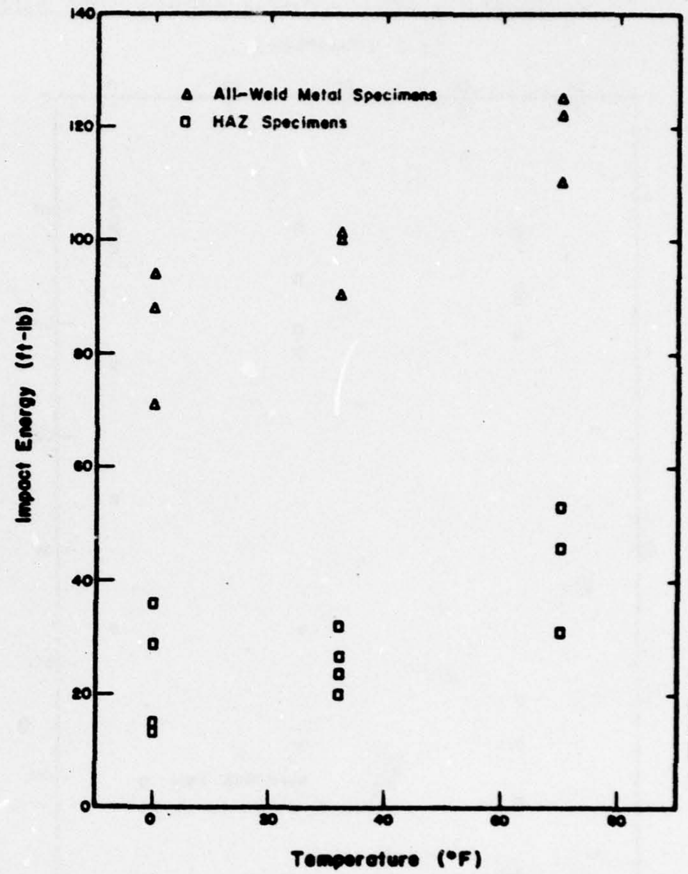

Figure 11. Charpy V-notch impact energy vs test temperature for A36 weldment-B7 (nugget area: 0.019 sq in. [12 mm²]).

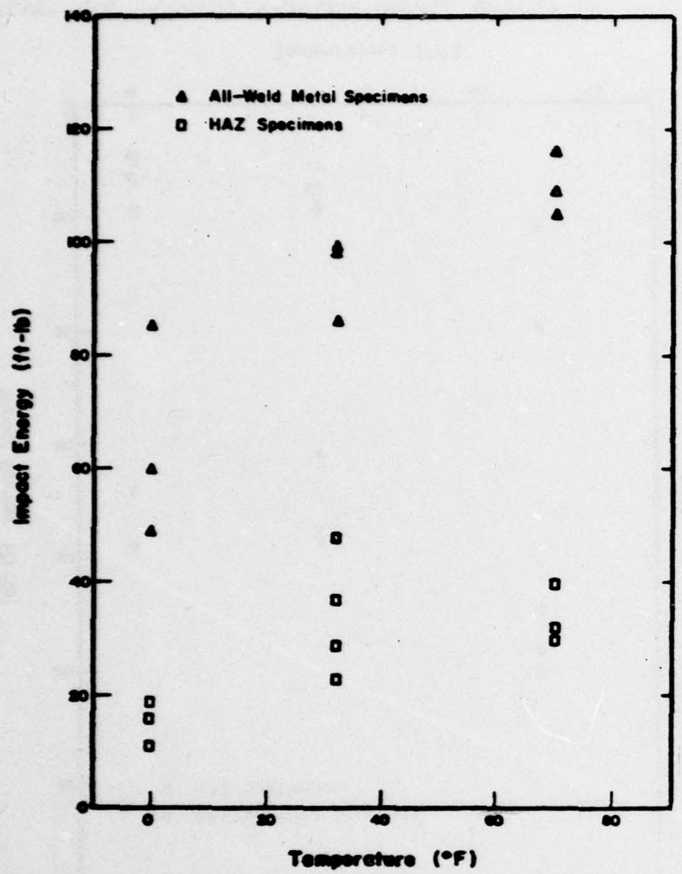

Figure 12. Charpy V-notch impact energy vs test temperature for A36 weldment-B8 (nugget area: 0.024 sq in. [15.5 mm²]).

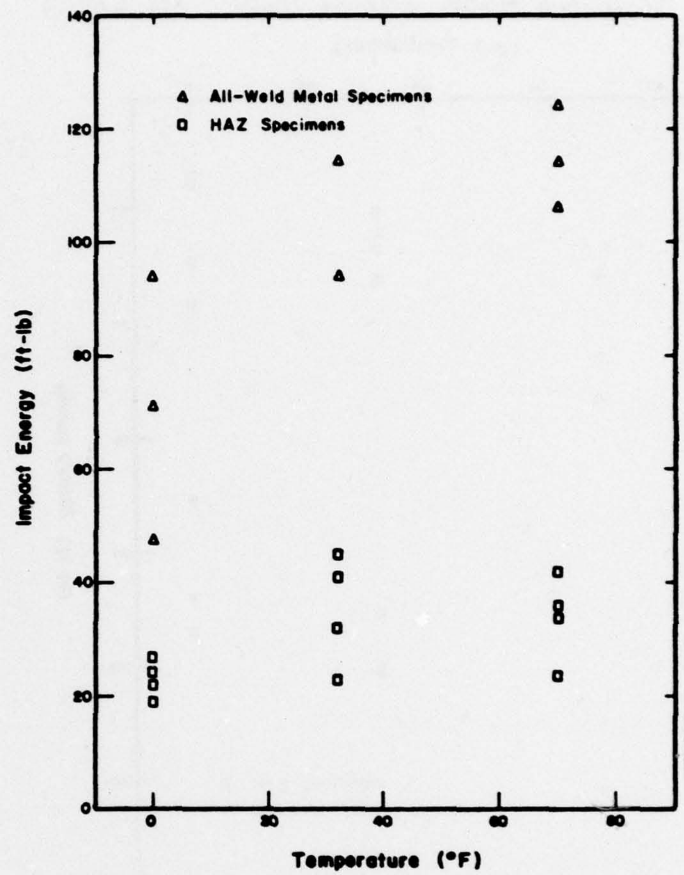

Figure 13. Charpy V-notch impact energy vs test temperature for A36 weldment-B9 (nugget area: 0.024 sq in. [15.5 mm²]).

metal impact results and the associated HAZ impact results. The HAZ results are lower than the all-weld metal results for all conditions. Barsom and Rolfe[15] have determined that the ductile-brittle transition temperature (DBTT) for A36 steel is 20°F (-6.7°C) with an energy of 5 ft-lb (6.8 J) and that the upper shelf energy is 50 ft-lb (67.8 J) at temperatures greater than 200°F (93.3°C). All the test temperatures used in this investigation were in the range of the DBTT.

Figures 14 and 15 present the average CVN energy at a test temperature vs the heat input and nugget area. The figures show no significant correlation between the CVN energy and either heat input or nugget area. Additional testing of the HAZ at higher temperatures is required to determine the exact DBTT for each heat input and nugget area used. Weld metal testing at lower temperatures is required to determine the DBTT and therefore any changes attributable to either the heat input or nugget area.

General

The data presented in this section are limited; more data with higher heat input and larger nugget area should be generated to provide a more complete picture of the yield strength and impact energy of the weldment.

Given the relatively low strength requirements for the A36 plate (36 ksi [253 MPa] yield strength), the weld metal yield strength need not be much more than the minimum requirements for the electrode used. The weld metal and base metal cannot have matching strength levels and still maintain the minimum weld metal requirements.

Over the range of nugget areas tested, the yield strength of both the weld metal and HAZ exceeded the nominal yield of A36 steel (37 ksi [255 MPa]), but based on the CVN-temperature results, these weldments may not perform satisfactorily in a low-temperature environment.

A516 Weldments

Tensile Test Results

Table 4 shows the tensile specimen testing results for the A516 steel weldments produced with E7018 electrodes. This is the AWS-recommended electrode and is of the same lot of electrodes used for the A36 weldments. Figure 16 shows a decrease in yield strength with heat input within a bandwidth of 6 to 10 ksi (41.4 to 68.9 MPa) -- the maximum at 78 ksi (537.9 MPa) and the minimum at 64 ksi (441.3 MPa) for

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[15] J. M. Barsom and S. T. Rolfe, "Correlations Between K_{IC} and Charpy V-Notch Test Results in the Transition-Temperature Range," Impact Testing of Metals, ASTM STP 466 (ASTM, 1970).

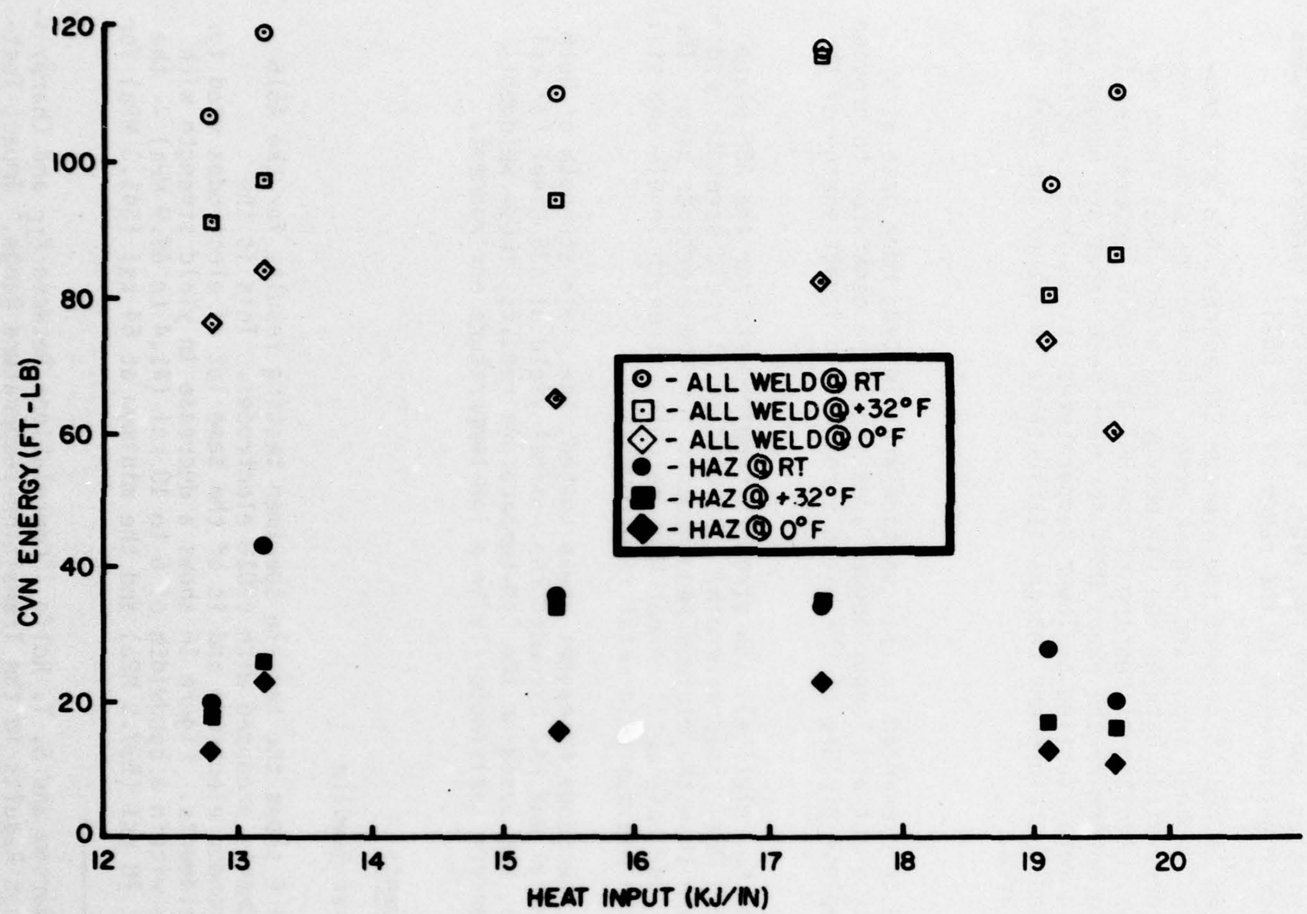

Figure 14. CVN energy vs heat input for A36 steel and E7018 weld metal.

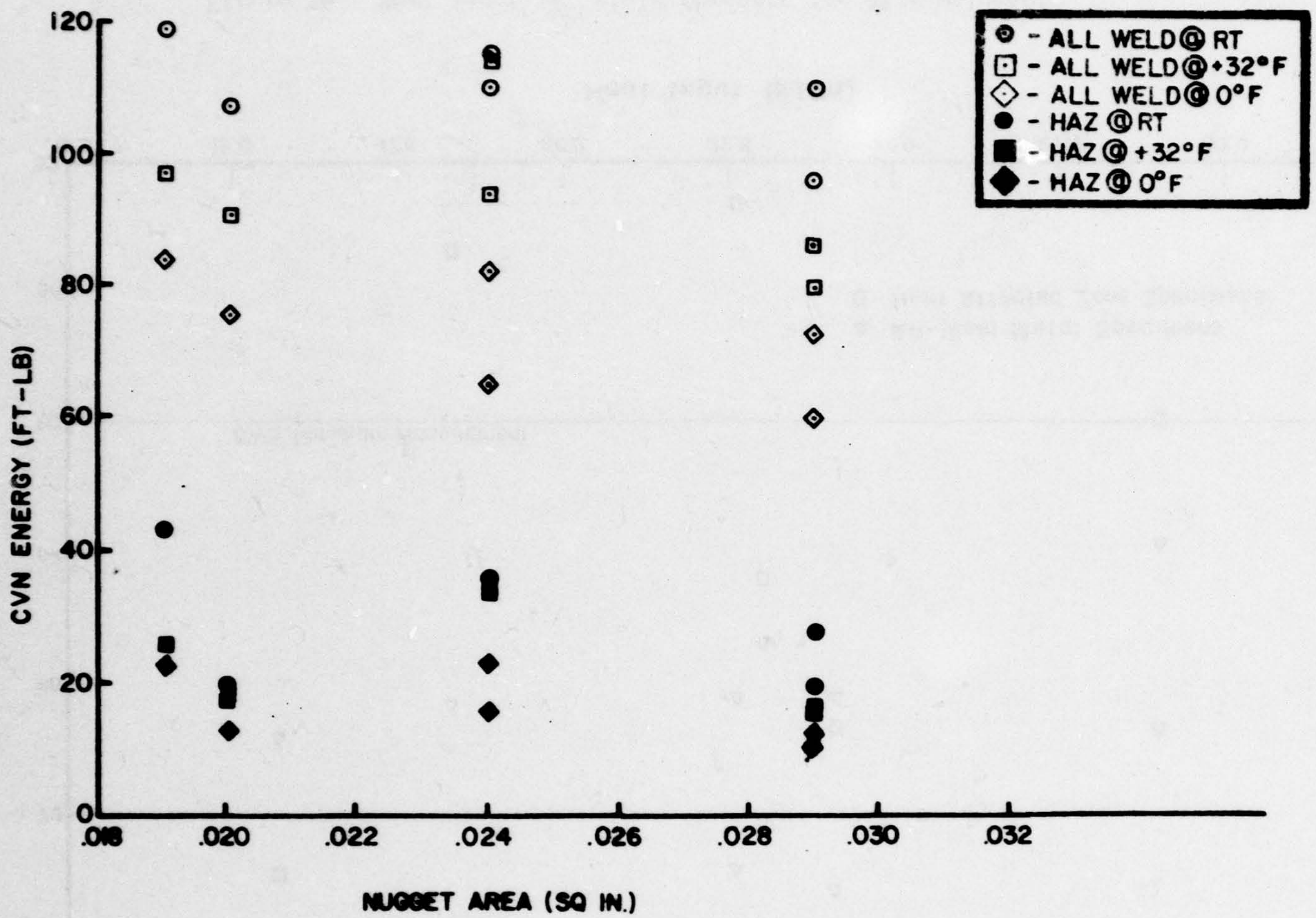

Figure 15. CVN impact energy vs nugget area for A36 steel and E7018 weld metal.

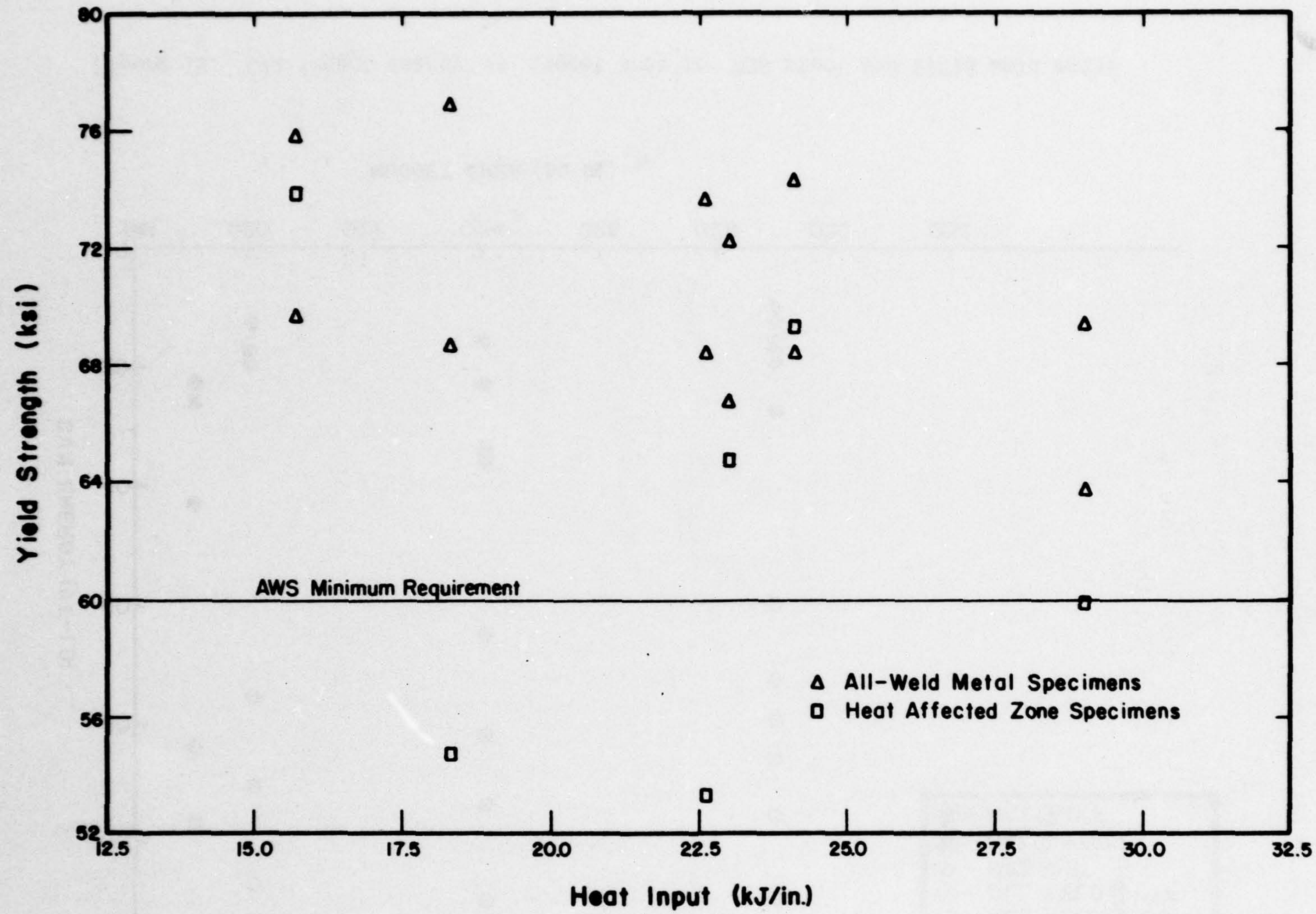

Figure 16. Heat input vs yield strength for A516 weldments.

the all-weld metal specimens. The HAZ data are too scattered to show a trend. In all cases, the HAZ yield strength in the above reported values for base metal yield strength is approximately 45 ksi (310.3 MPa).[16] Figure 17 reflects the same relationship for the all-weld metal specimens as in the case of the yield strength vs heat input. However, unlike the A36 weldments, the HAZ yield is still very scattered when plotted vs nugget area. Thus, the weldment response of the A516 steel is in sharp contrast to the A36 steel.

Impact Test Results

Figures 18 through 23 show the impact energy vs test temperature curves for the DT tests of A516 steel weldments. The data show lower energy values for the HAZ specimens, as occurred with the CVN response of the A36 weldments. The reported NDT temperature for A516 steel plate is about -100°F (-73.3°C) with approximately 30 ft-lb (40.7 J) of energy.[17] In most instances, the HAZ energy values are below the reported NDT energy level, which indicates that the NDT temperature of the HAZ has been increased. However, the exact NDT temperature determination would require more testing at higher temperatures.

Figures 24 and 25 present the DT energy vs the heat impact and nugget area. The general trend of the data is for DT energy to drop off as the heat input or nugget area is increased. Additional test points are required to confirm this conclusion.

General

The data presented in this section are limited and should include larger heat inputs and nugget areas to describe the yield strength and impact variances adequately.

These data indicate that both the yield strength and the impact energies of the weld metal and HAZ drop off with increased heat input and nugget area. If the additional testing confirms this general trend, then a trade-off will have to be made between high impact values and low weld metal yield strength levels. Again, as with the A36 weldments, the nominal yield strength (45 ksi [310.3 MPa]) is much lower than the minimum requirement of the weld metal (60 ksi [413.4 MPa]) and yield strengths cannot be matched without violating the weld metal specification minimum requirements.

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16 J. M. Barsom and S. T. Rolfe, "Correlations Between K_{IC} and Charpy V-Notch Test Results in the Transition Temperature-Range," Impact Testing of Metals, ASTM STP 466 (ASTM, 1970).

17 Specification for Mild Steel Covered Arc Welding Electrodes, AWS A5.1-6g (American Welding Society, 1969).

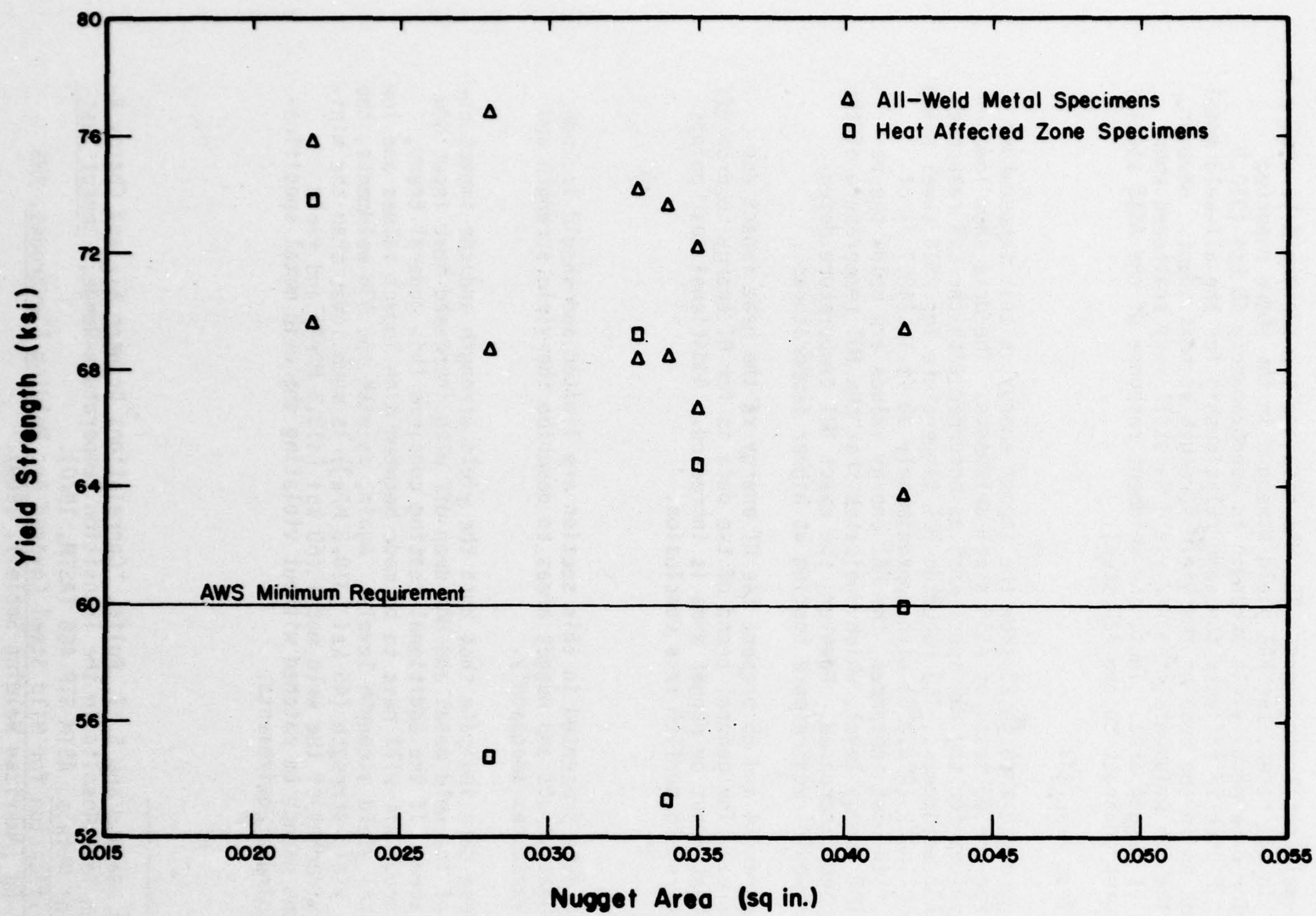

Figure 17. Nugget area vs yield strength for A516 weldments.

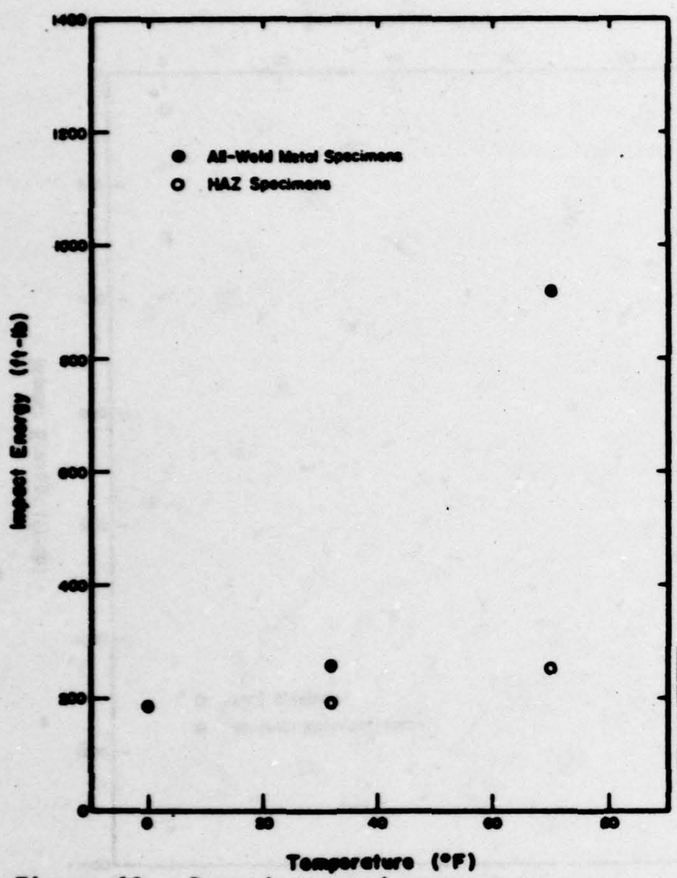

Figure 18. Dynamic tear impact energy vs temperature for A516 weldment-B10 (nugget area : 0.022 sq in. [14 mm^2]).

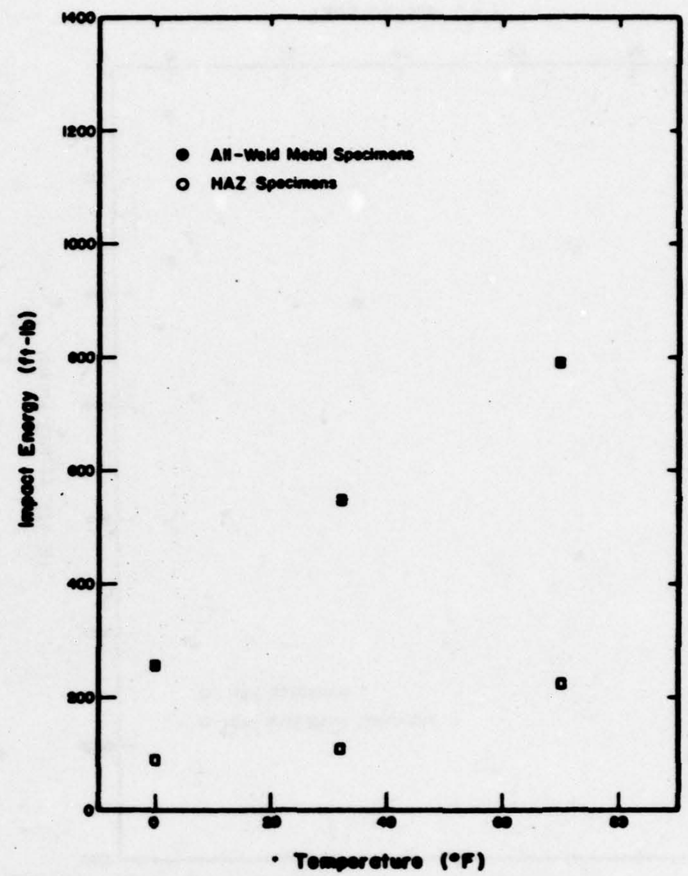

Figure 19. Dynamic tear impact energy vs temperature for A516 weldment-B11 (nugget area : 0.028 sq in. [18 mm^2]).

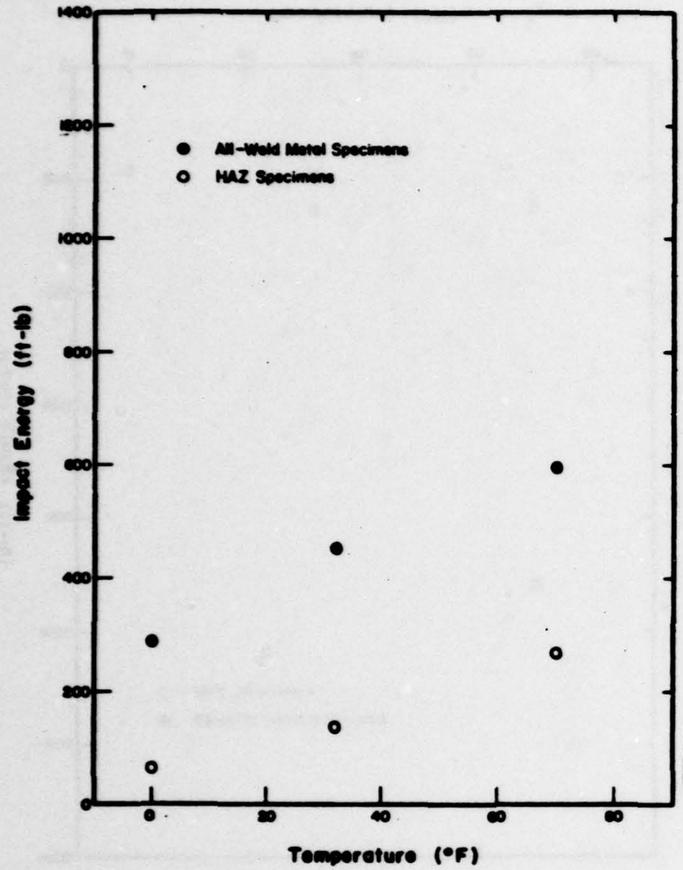

Figure 20. Dynamic tear impact energy vs temperature for A516 weldment-B12 (nugget area: 0.034 sq in. [22 mm^2]).

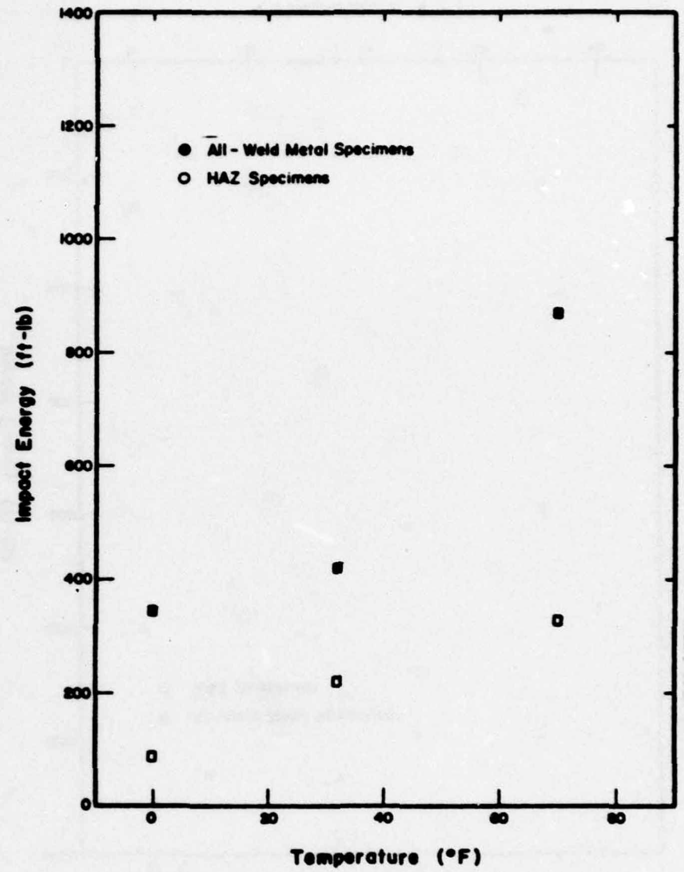

Figure 21. Dynamic tear impact energy vs temperature for A516 weldment-B13 (nugget area: 0.033 sq in. [21.5 mm^2]).

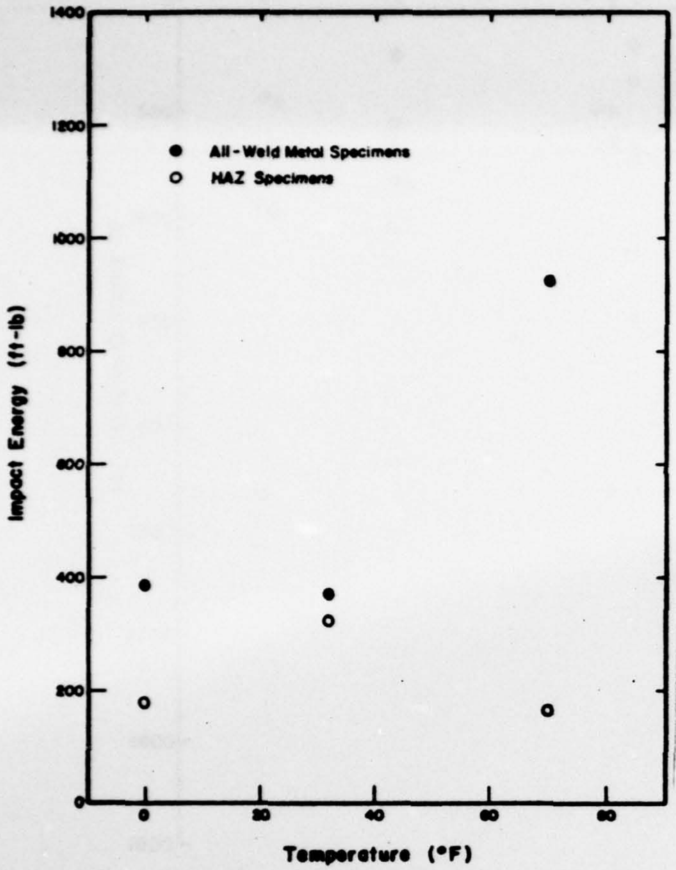

Figure 22. Dynamic tear impact energy vs temperature for A516 weldment-B14 (nugget area - 0.035 sq in. [25.2 mm^2]).

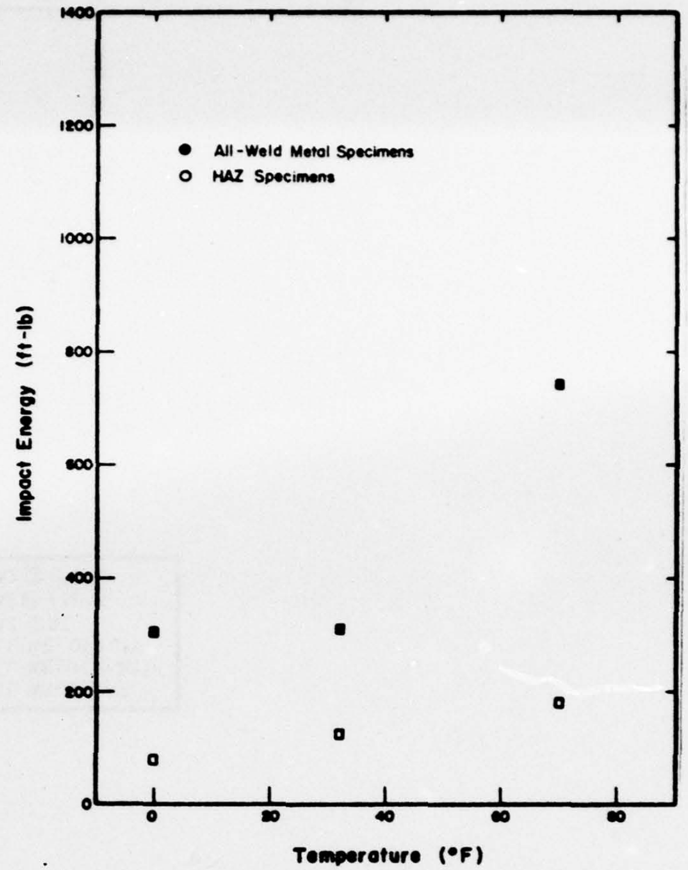

Figure 23. Dynamic tear impact energy vs temperature for A516 weldment-B15 (nugget area - 0.042 sq in. [27 mm^2]).

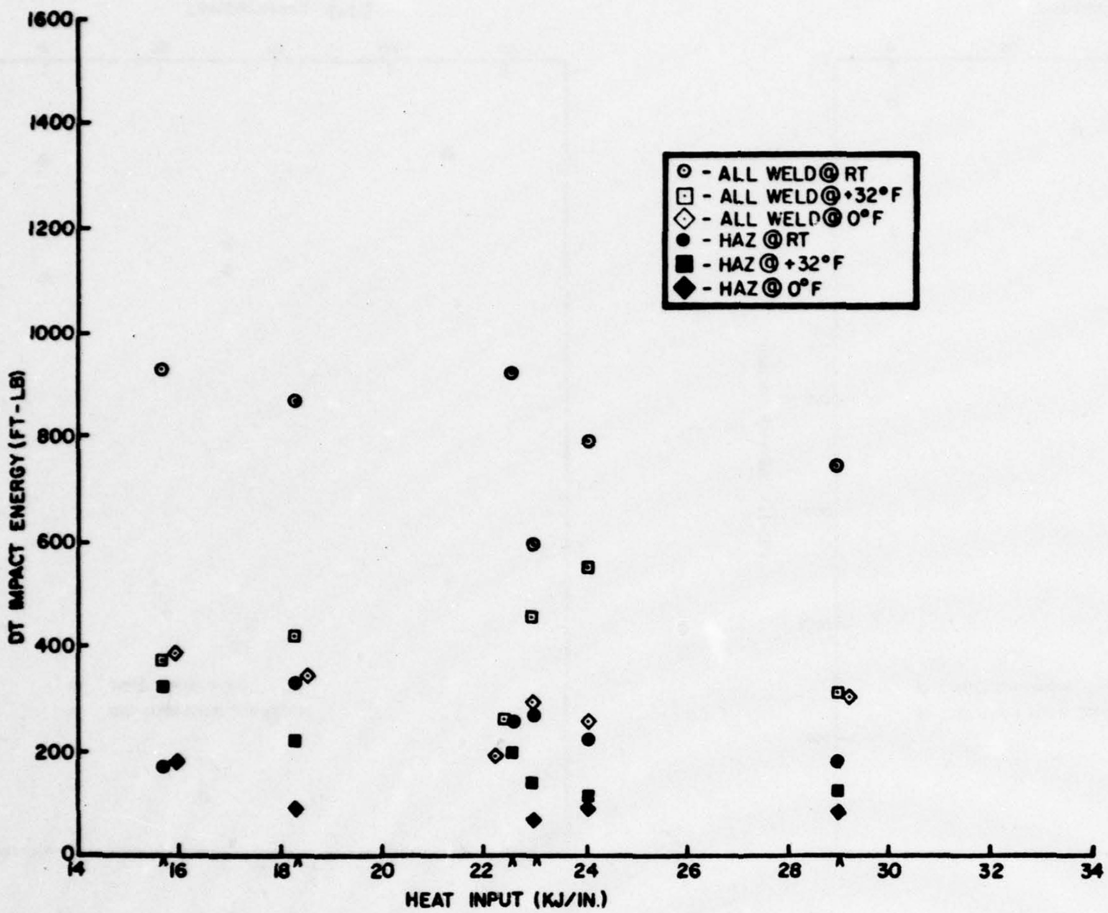

Figure 24. Dynamic tear energy vs heat input for A516 steel and E7018 weld metal.

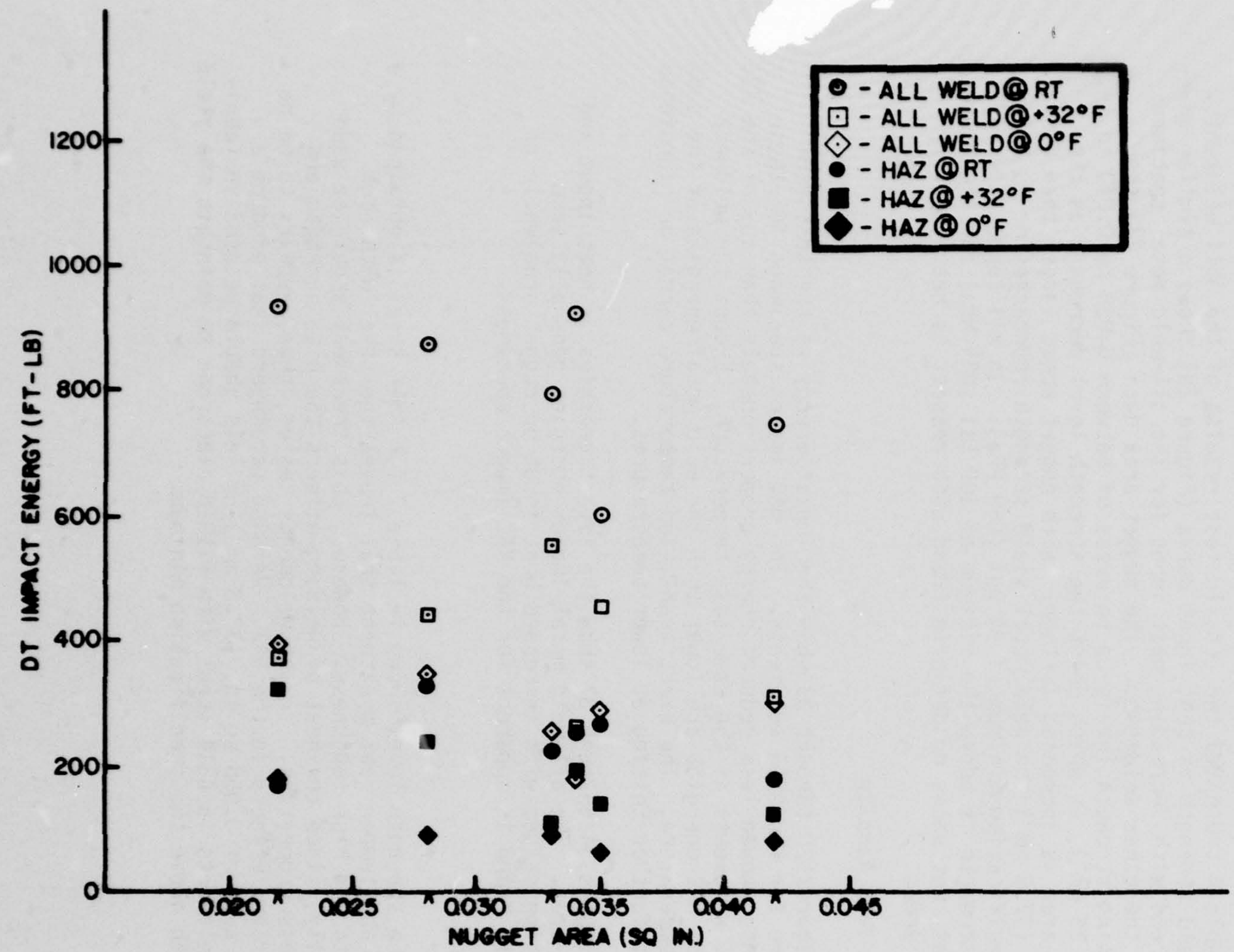

Figure 25. Dynamic tear impact energy vs nugget area for A516 steel and E7018 weld metal.

A514 Weldments

Tensile Test Results

Table 4 presented the tensile test results of the A514 weldments. The yield strength vs heat input curve (Figure 26) shows a similar downward trend with increasing heat input for the all-weld metal specimens as for the other weldments. The nugget area data (Figure 27) show increasing strength levels up to areas of between 0.038 to 0.040 sq in. (24 to 26 mm^2), at which point the strength level decreases as the nugget area is increased further. With nugget areas larger than 0.058 sq in. (37.5 mm^2) the weld metal yield strength approaches or is below the specification minimum of 97 ksi (669 MPa). In all cases, the HAZ yield strength is above the minimum of 100 ksi (689 MPa) for the plate material, but shows no definite trend with respect to heat input or nugget area.

Impact Test Results

Figures 28 through 33 show the impact energy vs the test temperature for the A514 weldments. The HAZ impact specimens for these weldments showed less reduced energy proportionately than any of the A36 or A516 weldments at the same test temperature. Except for weldment B19, the HAZ energies are lower than the weld metal energies at the same test temperature. The exact transition temperature cannot be pinpointed without further testing at lower temperatures.

Figures 34 through 37 show the impact energies vs heat input and nugget area. The all-weld metal impact energies generally show decreasing values with increased heat input or nugget area while no definite trend is apparent for the HAZ impact specimens.

General

The strength level shown in Table 2 for A514 steel is obtained by a quench and temper heat treatment that leaves the steel with high strength and high toughness. However, this treatment should be used carefully, since the heat of welding affects the high strength and toughness properties. In the weldments tested, there appears to be no deleterious effects in the HAZ. Welding parameters that produce a nugget area of 0.058 sq in. (37.5 mm^2) or less should be used to fabricate weldments in A514 steel with E11018 electrode to maintain the yield strength above the specification minimum.

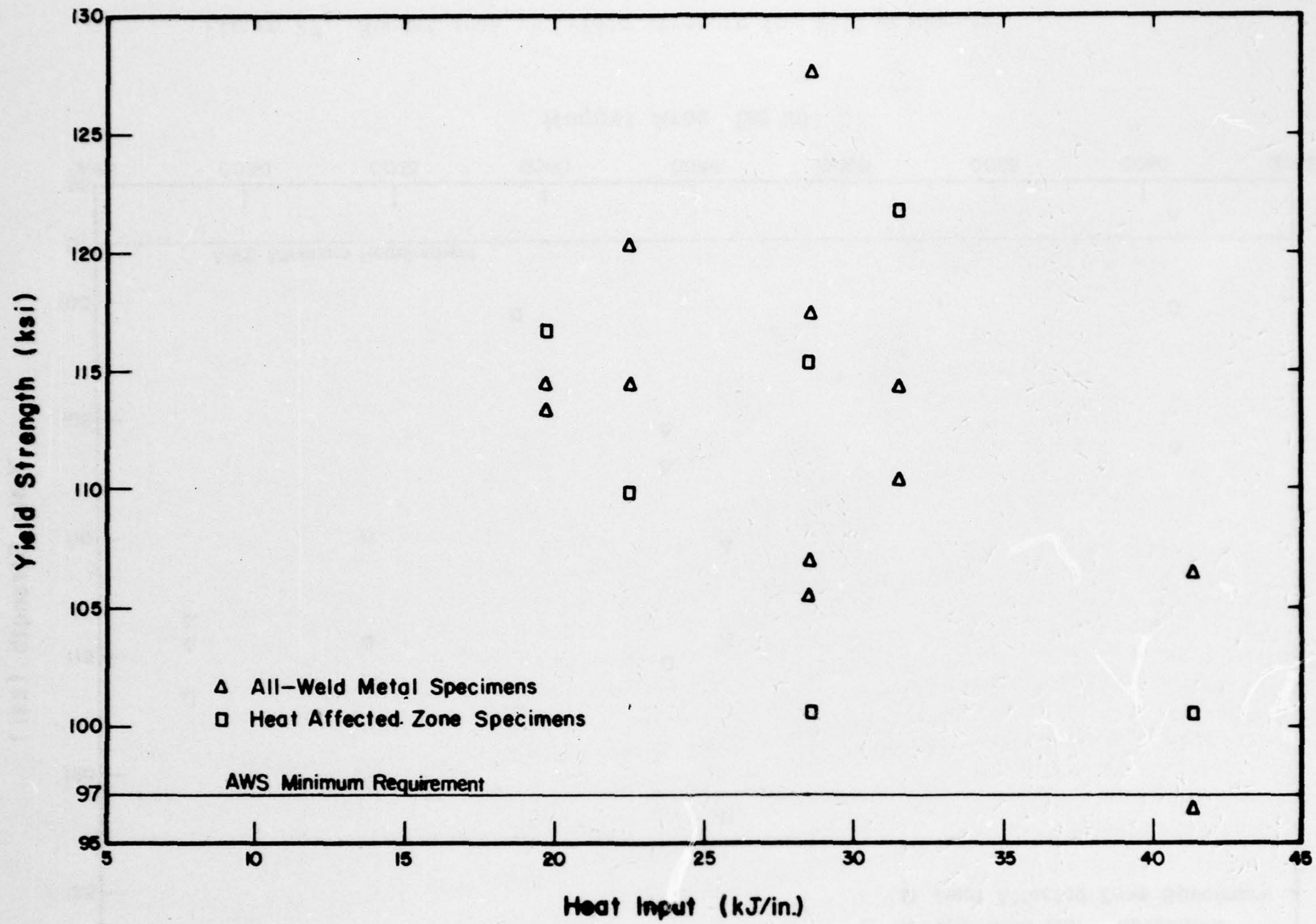

Figure 26. Heat input vs yield strength for A514 weldments.

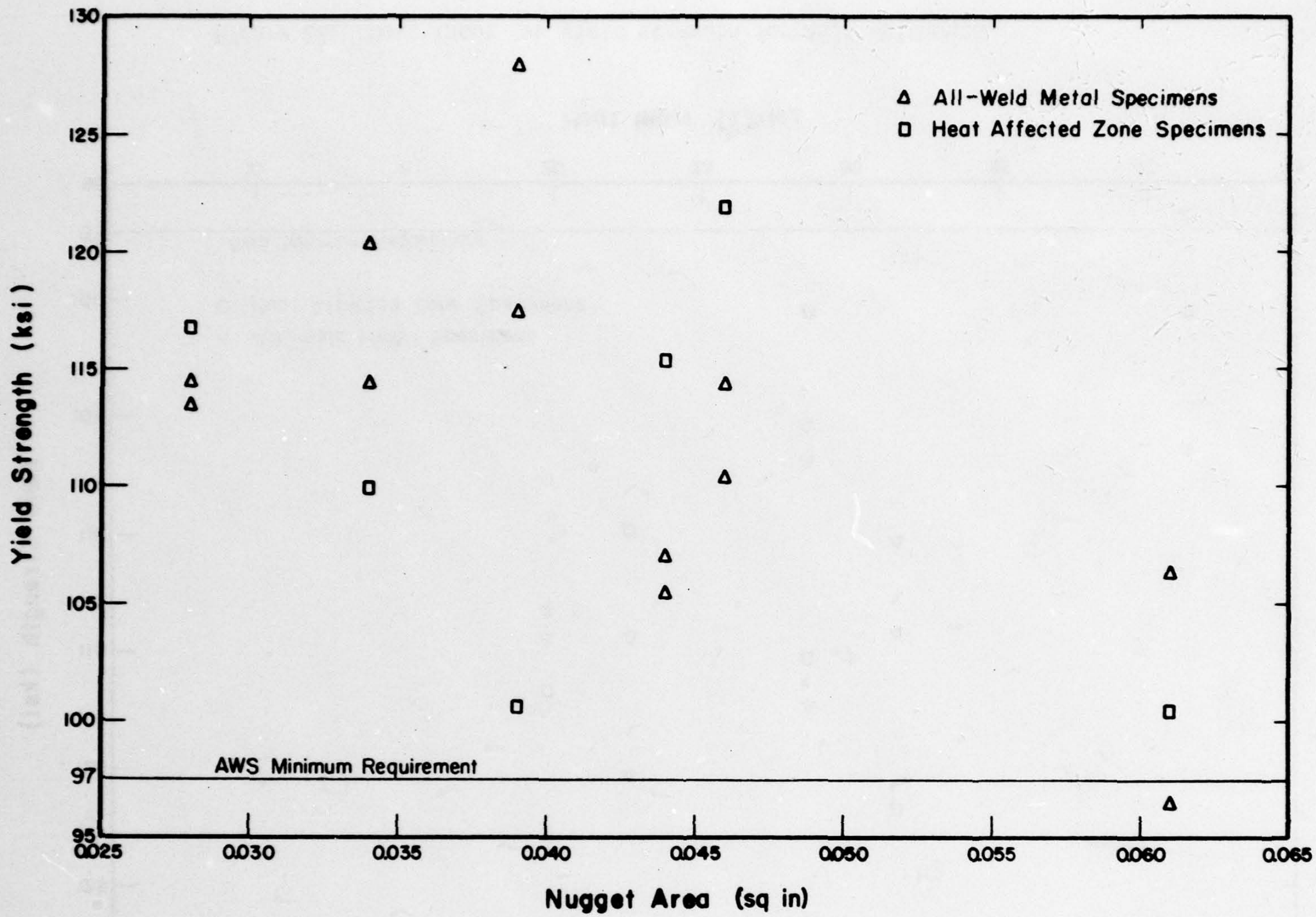

Figure 27. Nugget area vs yield strength for A514 weldments.

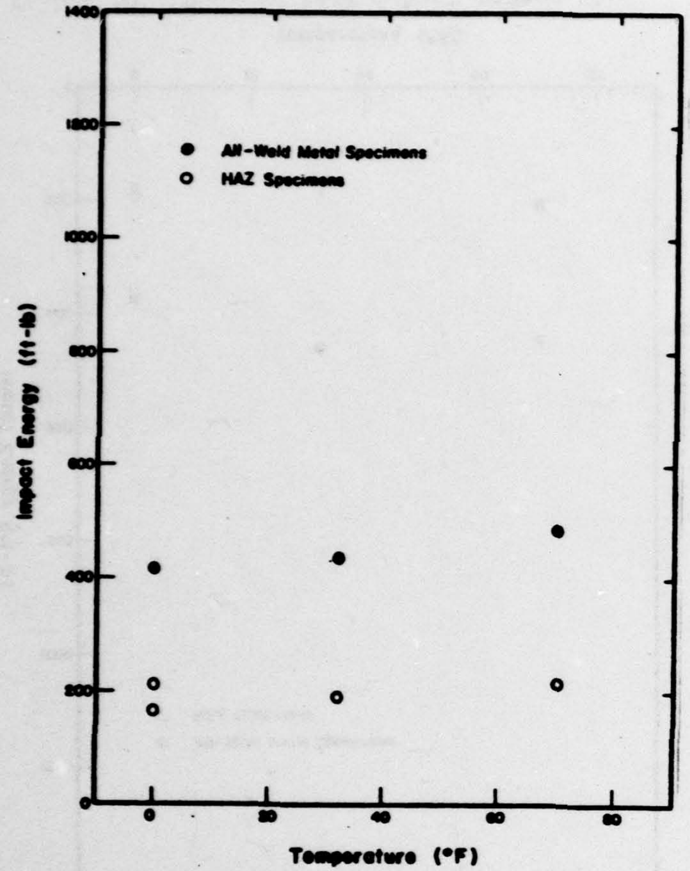

Figure 28. Dynamic tear impact energy vs temperature for A514 weldment-B16 (nugget area: 0.028 sq in. [18 mm^2]).

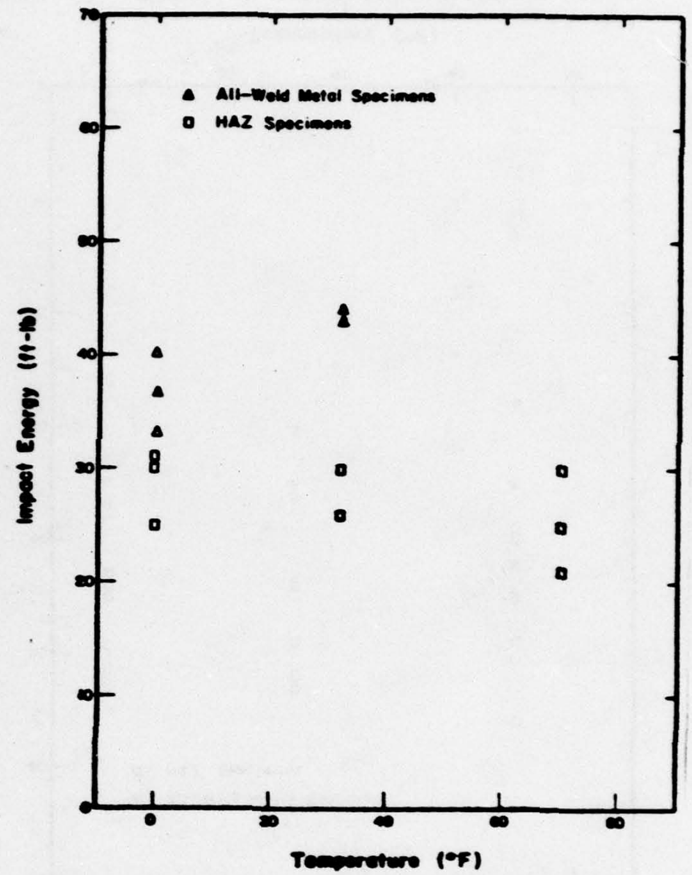

Figure 29. Charpy V-notch impact energy vs temperature for A514 weldment-B17 (nugget area: 0.034 sq in. [22 mm^2]).

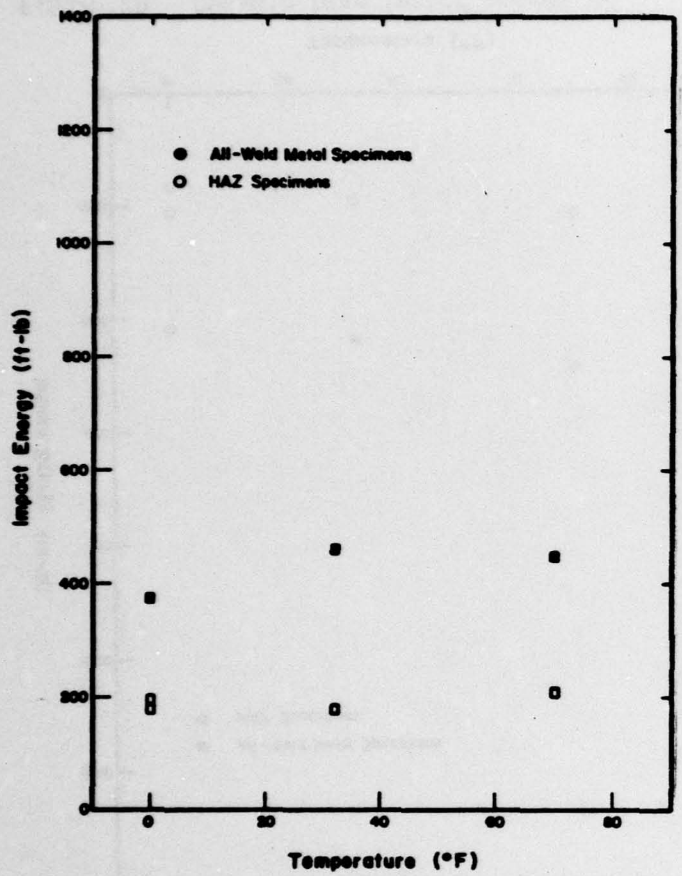

Figure 30. Dynamic tear impact energy vs temperature for A514 weldment-B18 (nugget area: 0.044 sq in. [28 mm^2]).

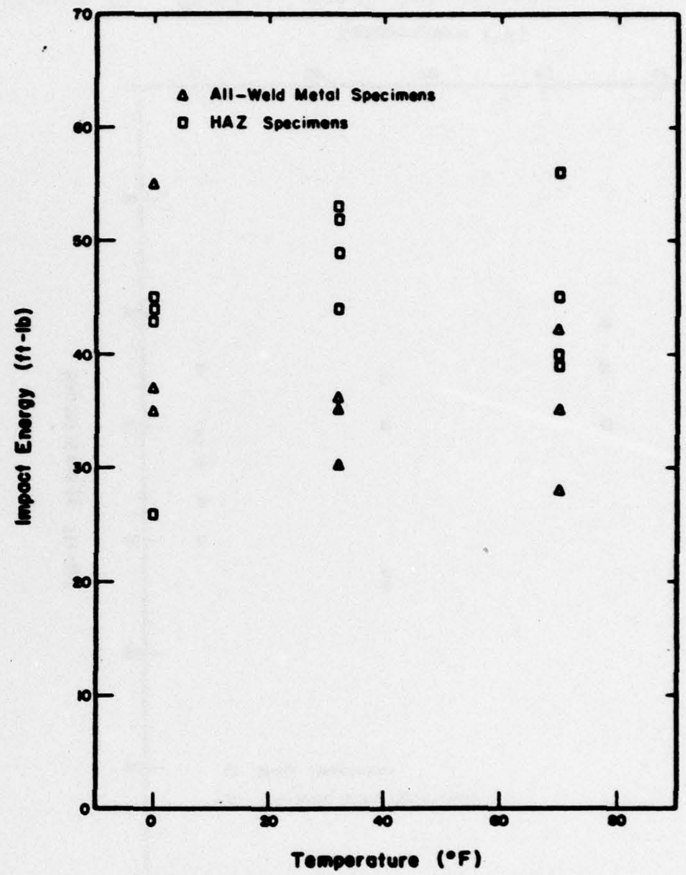

Figure 31. Charpy V-notch impact energy vs temperature for A514 weldment-B19 (nugget area: 0.039 sq in. [25 mm^2]).

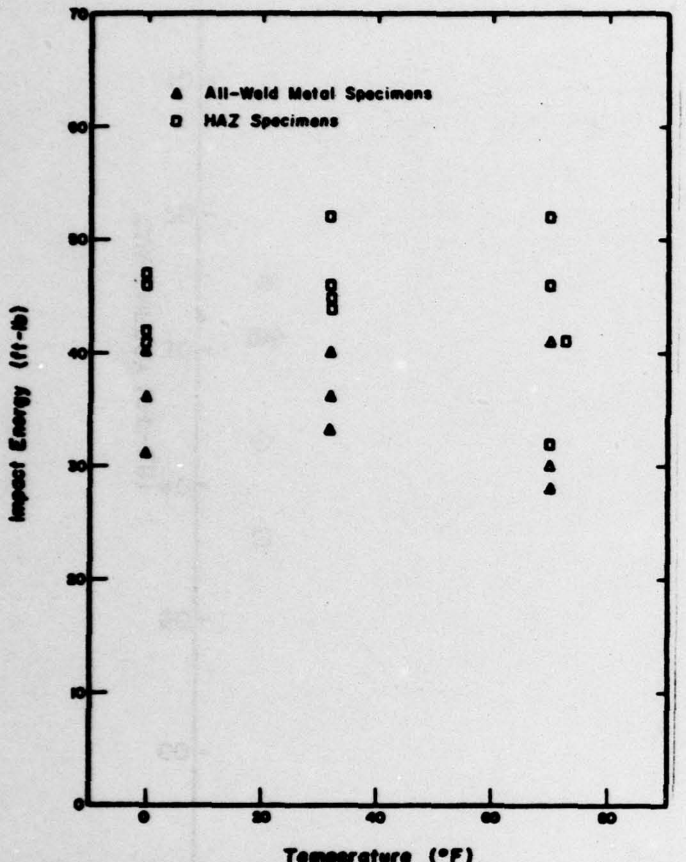

Figure 32. Charpy V-notch impact energy vs temperature for A514 weldment-B20 (nugget area: 0.046 sq in. [30 mm^2]).

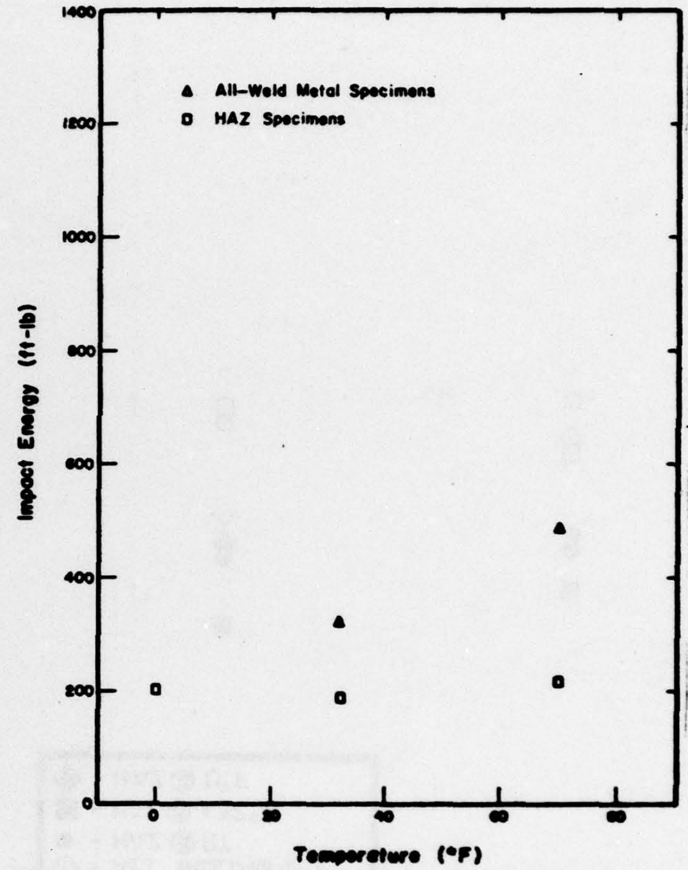

Figure 33. Dynamic tear impact energy vs temperature for A514 weldment-B21 (nugget area: 0.061 sq in. [40 mm^2]).

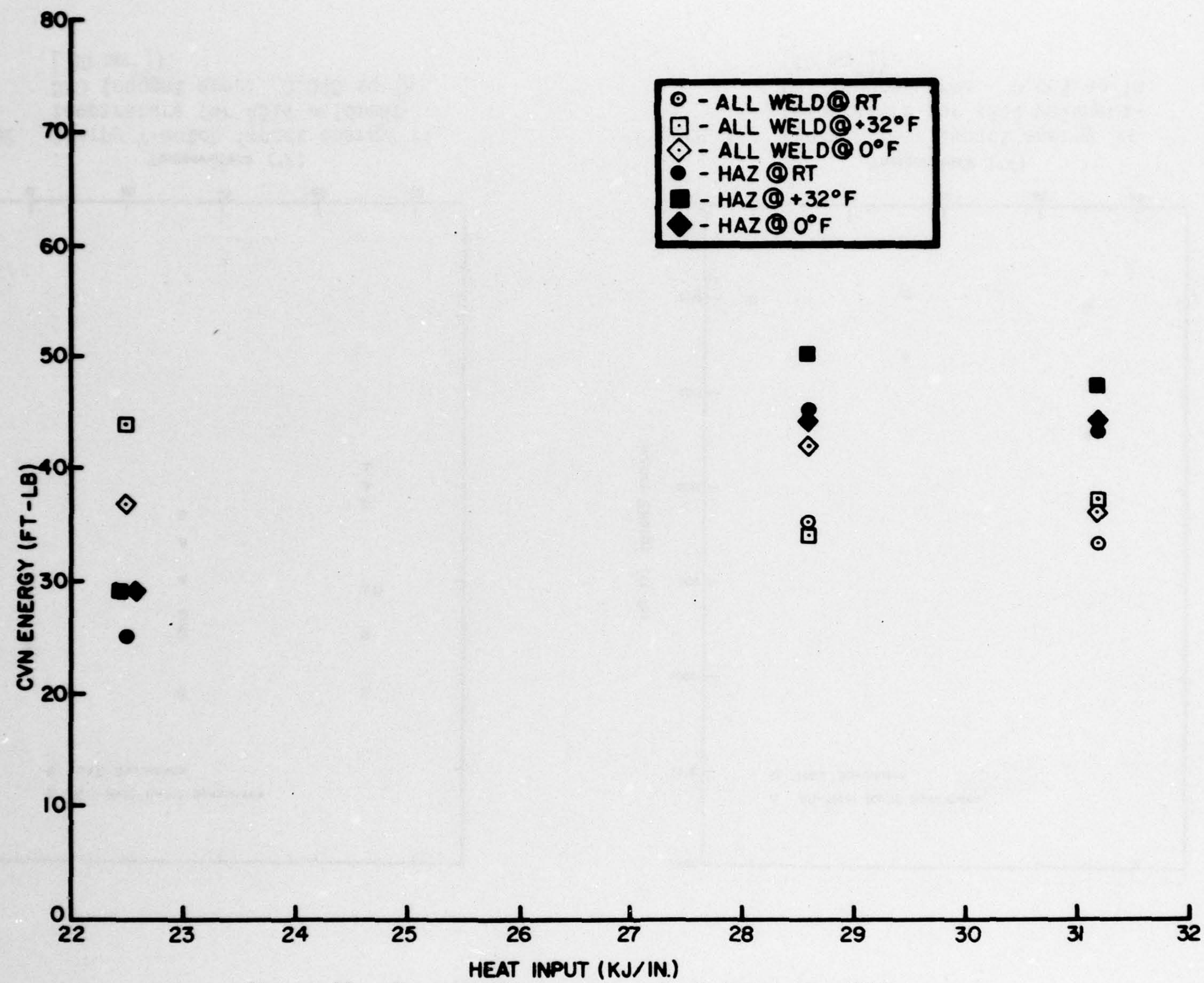

Figure 34. Average CVN energy vs heat input for A514 steel and E11018 weld metal.

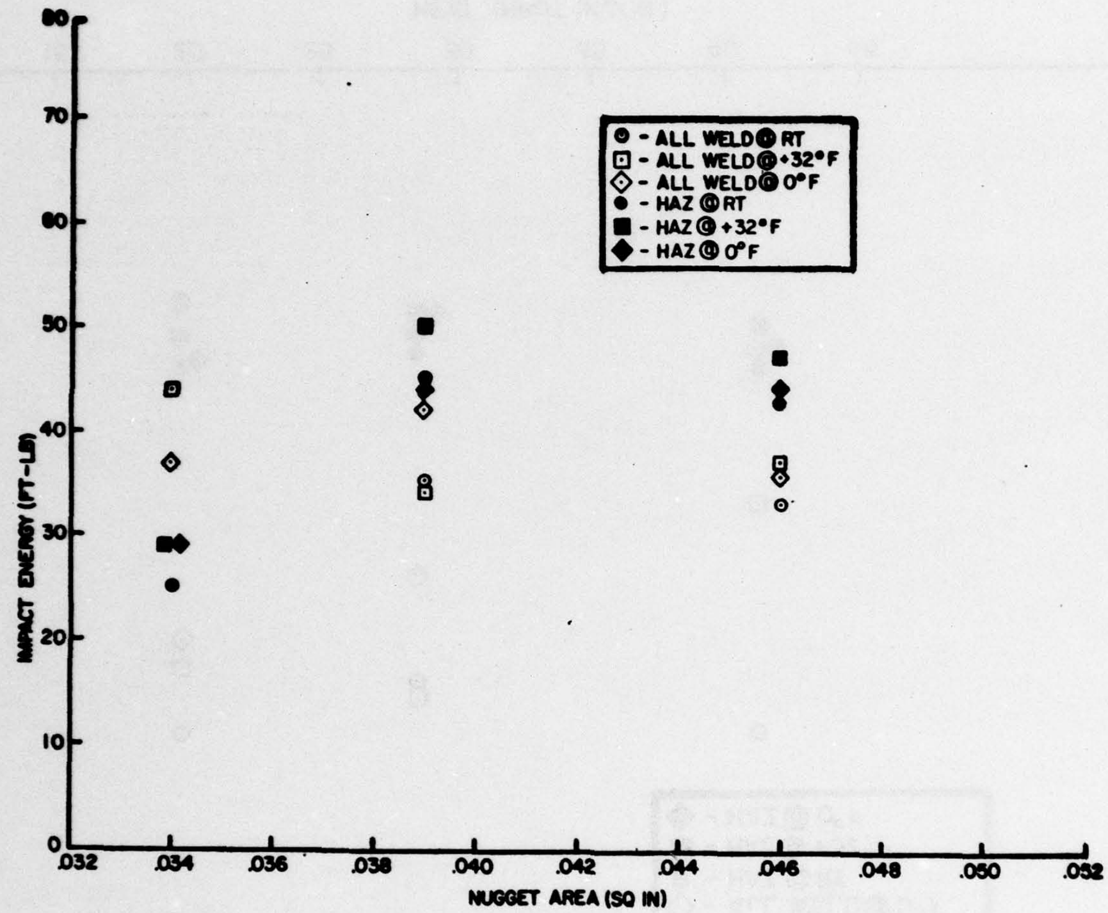

Figure 35. Average charpy V-notch energy vs nugget area for A514 steel and E11018 weld metal.

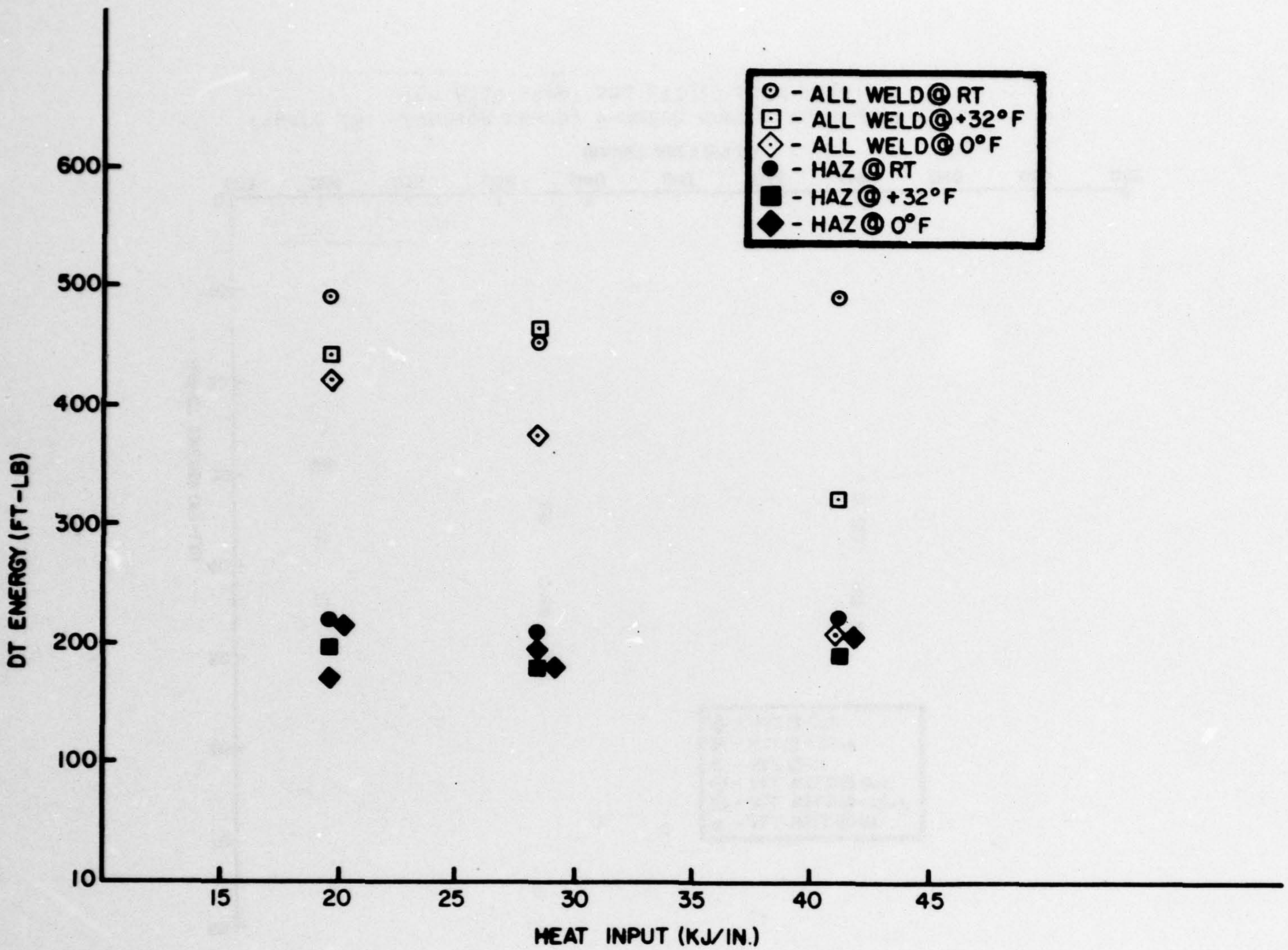

Figure 36. Dynamic tear energy vs heat input for A514 steel and E11018 weld metal.

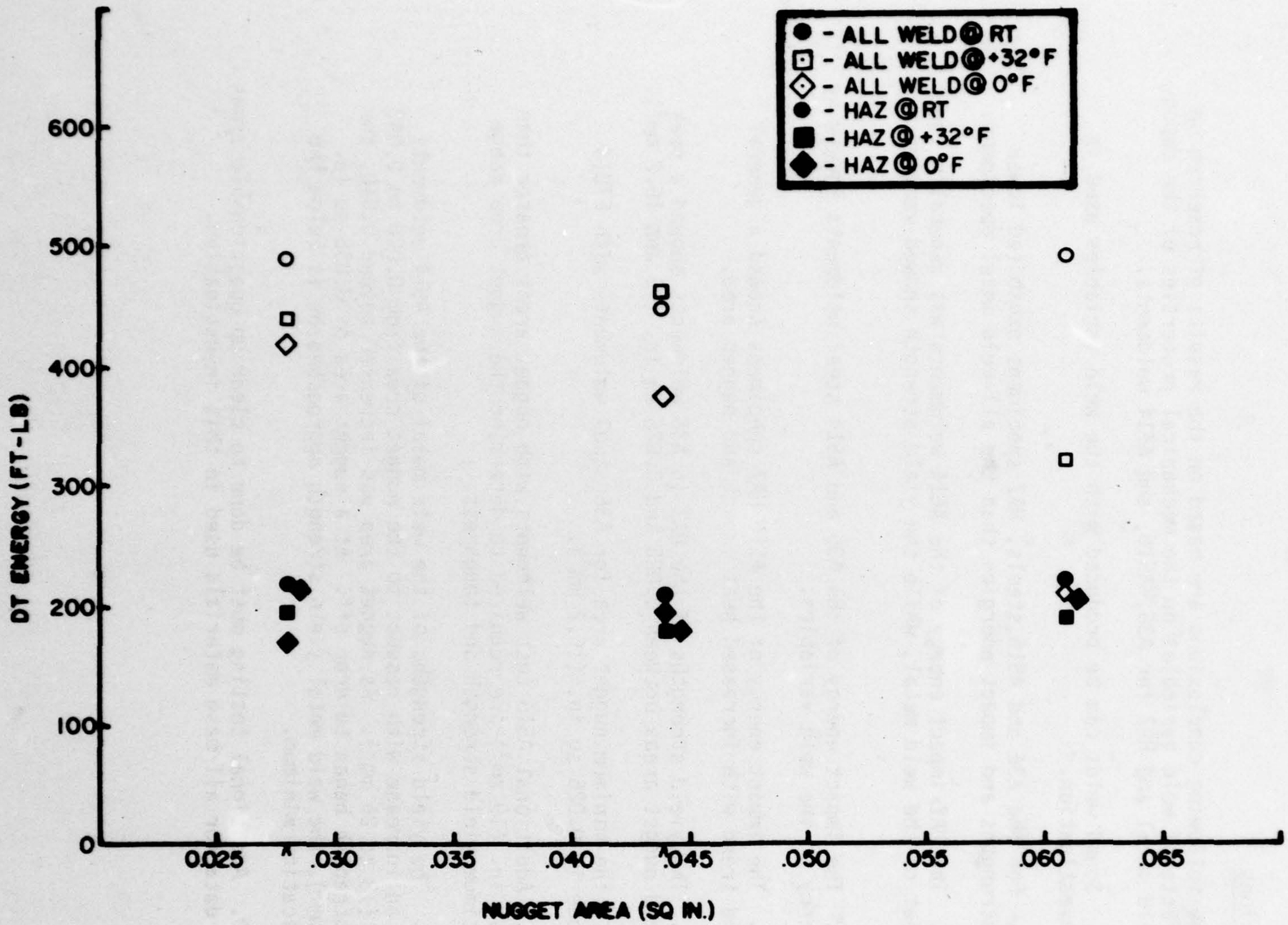

Figure 37. Dynamic tear energy vs nugget area for A514 steel and E11018 weld metal.

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions are based on the results of research on the effects of weld variables on the mechanical properties of the deposited weld metal and HAZ for A36, A516, and A514 weldments.

1. Sound welds can be produced with the weld variables used in this investigation.

2. For the A36 and A516 steels, HAZ specimens exhibited lower yield strengths and impact energies than the all-weld metal specimens.

3. The HAZ impact energy of the A514 weldments was generally lower than that of the weld metal, while the yield strength showed varying results.

4. The impact energy of the A36 and A514 steel weldments showed no dependency on the weld variables.

5. The impact energy of the A516 HAZ specimens showed a general downward trend with increased heat impact and nugget area.

6. The yield strengths of the HAZ in A36 weldments showed a peak with weld nugget areas between 0.023 and 0.025 sq in. (15 and 16.2 mm^2).

7. The minimum nugget area for A36 steel weldments with E7018 electrode is 0.025 sq in. (16.2 mm^2).

8. Additional A516 test weldments with nugget areas greater than 0.030 sq in. (19 mm^2) are required to determine the nugget area range for optimum yield strength and toughness.

9. The yield strengths of the weld metal of the A514 weldments showed an increase with respect to the nugget area from 0.028 to 0.040 sq in. (18 to 26 mm^2). As nugget area was increased beyond 0.040, the yield strength began to drop off. At a nugget area of 0.058 sq in. (37.5 mm^2), the weld metal yield strength approaches or is below the specification minimum.

10. Additional testing must be done to clear up questionable areas in the data for all base materials used in this investigation.

Recommendations

1. Additional testing is required to establish the nugget area values necessary to assure A36 and A516 steel weldments the best toughness and yield strength of the weld metal and base metal (HAZ).

2. The welding variables for A514 steel should be chosen to produce nugget areas between 0.025 and 0.058 sq in. (16.2 and 37.5 mm^2).

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